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Green Hydrogen in Mexico: towards a decarbonization of the economy

Volume VI: Local value chain analysis and export potential for green hydrogen

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Abbreviations

BEV	Battery Electric Vehicle
CAEX	Camiones de Extracción, Mining haul trucks
CAPEX	Capital Expenditures
CFE	Comisión Federal de Electricidad
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FTE	Full-Time Equivalent Job
GHG	Greenhouse Gas Emissions
HDV	Heavy-Duty Vehicle
HRS	Hydrogen Refueling Station
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
INECC	National Institute of Ecology and Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
MW	Megawatt
NDC	Nationally Determnded Contributions
NG	Natural Gas
O&M	Operation & Maintenance
OEM	Original Equipment Manufacturer
PEMEX	Petróleos Mexicanos
SENER	Secretaría de Energía, Ministry of Energy
SDGs	Sustainable Development Goals of the United Nations
SEMARNAT	Secretaría del Medio Ambiente y Recursos Naturales, Ministry of the Environment and Natural Resources
SENER	Secretaría de Energía, Ministry of Energy
SMR	Steam Methane Reforming (H_2 production)
UNFCCC	The United Nations Framework Convention on Climate Change

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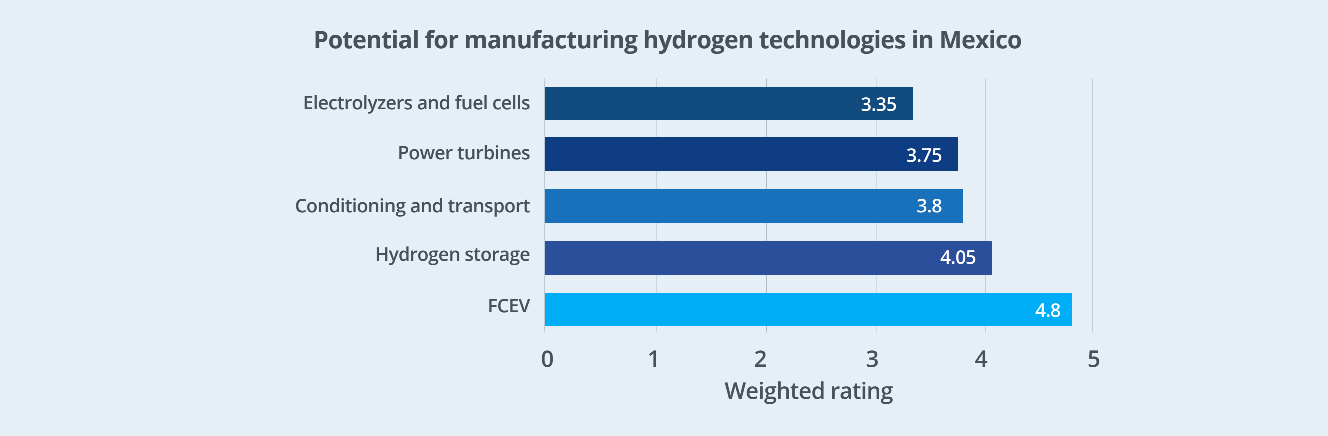
Executive summary

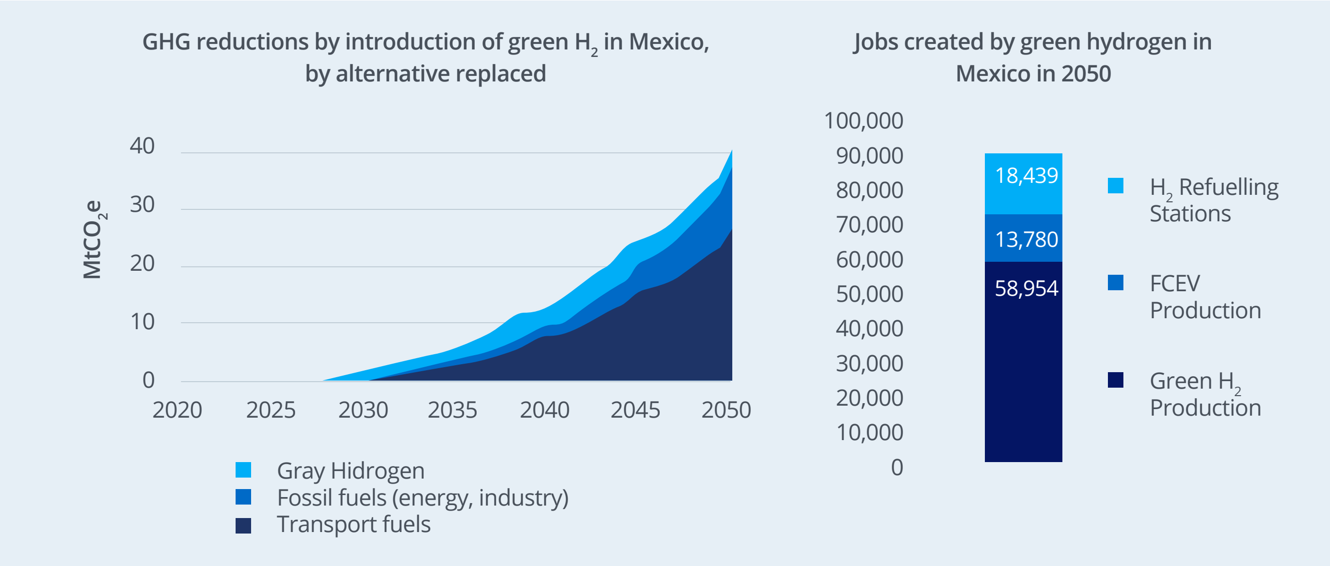
The hydrogen economy in Mexico could have significant impacts across a broad range of areas, including manufacturing, climate mitigation, job creation, business opportunities locally and in international trade, regulatory and financial strengthening, as well as capacity building.

Figure 1. Ranking of competitiveness for the manufacture potential of H_2 technologies in Mexico.



The analysis of hydrogen technologies manufacturing, shows Mexico as a country with potential to be competitive in the manufacture of hydrogen power turbines as well as conditioning, transport, and storage equipment. The automotive industry could continue to thrive in the country, leveraging on a robust manufacturing ecosystem to adopt new hydrogen FCEV technologies. Mexico displays the potential to position itself as a leading manufacturer of FCEVs worldwide.

Figure 2. GHG emissions reductions and jobs created by green hydrogen in Mexico.

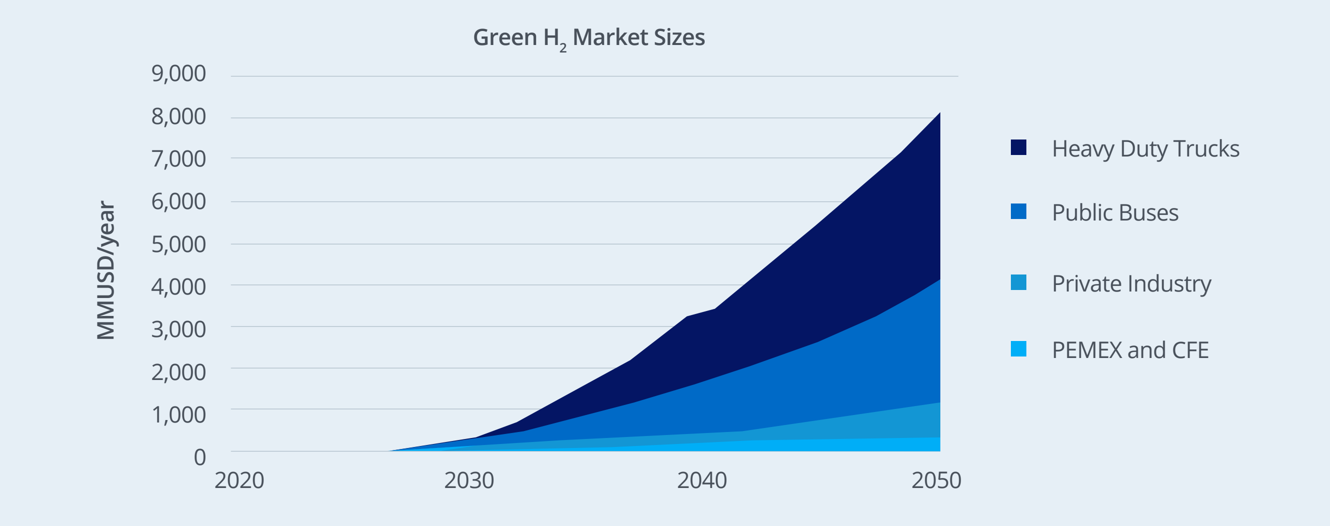


Close to 300 Mton CO_2e could be avoided by introducing green hydrogen in Mexico by 2050, of which two-thirds correspond to replacing fossil fuel consumption by fuel cell electric vehicles (FCEV) for public and freight transport. The CO_2 avoided by the introduction of green hydrogen by PEMEX in refineries and ammonia production in Mexico could reach more than 3.2 million $tonCO_2e$/year by 2050. Replacing fossil fuels with green hydrogen for applications in power generation and industry has the potential of reducing up to 7.6 million $tonCO_2e/year$ in 2050. By 2050, substituting ICEVs with FCEVs and diesel with syn-fuels could reduce GHG emissions by up to 26.7 $tonCO_2e/year$.

In job creation, over 90,000 people could work in hydrogen in Mexico by 2050. The largest potential for job creation is in the production of hydrogen itself and the required infrastructure. The second largest area would be in the hydrogen refueling infrastructure, and thirdly, the automotive industry for heavy-duty FCEV production.

As for market creation and investment, the joint expected impact for PEMEX and CFE is of roughly 100 million USD per year by 2030 and more than 1.3 billion USD yearly by 2050 to supply their hydrogen demand. The largest projected opportunities in hydrogen for the private industries are in FC CAEX and mineral ore reduction, which jointly account for nearly 80% of the economic impact valued at 800 million USD/year by 2050. Cumulative investments for supplying hydrogen to PEMEX and CFE are projected in close to 2.6 billion by mid-century, and in nearly 8.5 billion to supply the private industry.

Figure 3. Green hydrogen market size projections in Mexico for energy and industrial uses (PEMEX, CFE, and private industries) and for public and freight road transport.



Mexico's abundant renewable energy resources and privileged position provide it with a great potential to export hydrogen to international markets. As early as 2030 more than 300 million USD of green H_2 could be exported overseas. When compared to potential large exporters of green hydrogen, Mexico is placed as a competitive long-distance exporter to Europe and Asian markets, given a low projected green H_2 production cost and its privileged geographic position next to the US and with access to both the Atlantic and the Pacific Oceans at a northern latitude, allowing it to compete closely with Chile and Australia. In 2030, Mexican green H_2 could be delivered in Europe at roughly 6 USD/kg and by pipeline at 2.5 USD/kg to bordering US states.

Recommendations and Capacity Building

Policies and Regulation:

Mexico should update its climate change policy, recognize hydrogen's potential benefits, and develop state and national roadmaps to support its deployment. A National Hydrogen Strategy with defined targets and actions to achieve them along with hydrogen-specific regulations for its different applications, has proven internationally to be a practice to boost the hydrogen economy.

Economic and Political Context:

By promoting renewable energies from a political and regulatory standpoint, measures are put in place that facilitate access to energy infrastructure for the development of hydrogen projects, and foster collaboration between specialized hydrogen companies and PEMEX and CFE. Guarantees of Origin systems for green hydrogen should be put in place to stimulate its export and incentivize its adoption recognizing its environmental benefits.

Technology and Human Capital:

Provide funding and financial assistance to hydrogen technology development, scale-up, and implementation. These could come from public, private, multilateral banking sources or a combination of them.

Actively communicate the workings and benefits of green hydrogen to all stakeholders, create learning missions, and international partnerships that include knowledge transfer programs on topics regarding Green Hydrogen.

Finally, set up a strategy to develop qualified talent in green hydrogen by fostering dedicated training, academic-industry partnerships, and international cooperation in higher education, research, development, and innovation.

International Experiences:

A compilation is made of international best practices and recommendations to enable the development of green hydrogen projects. Many of these overlap with those described above, reflecting of their alignment with international experience and best practices.

Capacity Building:

Mexico has many intellectual, financial, and legal capabilities in the energy and industry sectors already well developed. However, the adoption of the green hydrogen economy will demand the country do capacity building by developing new qualified human resources, as well as expanding financial, legal, and commercial capabilities.

1. Introduction

This report presents a diagnostic for the development of a manufacturing industry for green hydrogen technologies in Mexico by identifying the country's strengths and areas of opportunity to develop the manufacture infrastructure for technologies within the green hydrogen value chain. It focuses on electrolysers and fuel cells, equipment for the conditioning, transport, and storage of hydrogen, hydrogen power turbines, and hydrogen fuel cell electric vehicles (FCEV).

It also evaluates the social, environmental, and economic benefits of creating a green hydrogen value chain in Mexico, providing a quantification of GHG emissions reduction, inputs on job creation, and economic benefits of hydrogen adoption in the country.

Regulatory and financial barriers to the development of a green hydrogen economy are diagnosed, and recommendations are made to boost hydrogen production and use in Mexico by addressing them. A similar analysis is done to diagnose and enhance the capacities to be developed in Mexico for a more accelerated deployment of hydrogen infrastructure.

Finally, the potential production and export of green hydrogen from Mexico to contribute to international hydrogen and energy transition needs is presented, with a quantification of the country's potential for exporting hydrogen and business cases.

Given the diversity of the analyses performed, the methodology followed for each of the analyses is detailed in the corresponding chapter.

2. Diagnostic for development of a manufacturing industry for green hydrogen technologies in Mexico

The advent of the hydrogen economy locally and globally could present opportunities for Mexico in the manufacture of technological components along the green hydrogen value chain, from production to storage, conditioning, transport, and end use for power generation or mobility applications.

In order to diagnose the development of a manufacturing industry for green hydrogen technologies in Mexico, a methodological process was followed to assess the country's conditions and capabilities across different dimensions and hardware groups. First, the country's potential and capabilities to manufacture a categorized types of hydrogen technology components and second, the segments to identify the most competitive positions for business opportunities within the country were compared and ranked.

The hydrogen infrastructure components are grouped into hardware categories according to the type of devices and place in the value chain into: electrolysers and fuel cells, conditioning and transport equipment, hydrogen storage, power turbines, and fuel cell electric vehicles (FCEV).

2.1. Manufacturing Potential Evaluation Criteria

Each segment is evaluated for Mexico across seven dimensions, which are shown in the next column. For each dimension, the country is given a score going from least competitive (1) to most competitive (5), which allows to build radar charts to map each segment's potential and obtain a weighed rating to rank them. Not all dimensions are weighted equally, giving a large value to those considered most relevant, and a lower one to those with a smaller attributed impact.

Natural resources availability refers to whether if Mexico is a producer, exporter, or importer of the key natural resources required to manufacture the technology components for a given application, as well as the difficulty or ease to obtain those resources when not produced nationally.

Access to the supply chain indicates the existence or ease of development of the value chain within the country for the integration of the given components, which could range from an established presence or ease of access to difficulty or even blockages to the development of the supply chains in the segment.

Talent & human resources talks about the presence of qualified personnel in similar or related value chains that could eventually participate in the manufacture of the studied components, from being non-existent to being acknowledged with international renown.

Installed production capacity indicates if some components within the value chain or closely related ones are already produced in Mexico, with the associated manufacturing infrastructure and experience. This ranges from lacking any related infrastructure to having an existing manufacturing base for related equipment.

Manufacturing development ecosystem aims to quantify how favorable the conditions are for the development of the industry, how established and quickly growing it is in Mexico, and if plans exist to strengthen capabilities; going from unfavorable conditions to having an established and growing industry in the sector.

National experience in developing new value chains indicates the level of experience in the country for developing new value chains in related sectors, and how current and suitable it could be for hydrogen technologies, ranging from zero to broad and recent experience in the segment.

Trade context with potential consuming countries refers to the status of active trade relationships of Mexico with countries with large potential as consumers for the technology component, from difficult to active relationships and the existence of trade agreements with customer countries.

Table 2-1. Dimensions, rated weigh, and qualitative description for their lower and higher values.

Dimension	Weight	Lower Rank (1)	Higher Rank(5)
Natural resources availability	10%	Mexico is a net importer of valuable resources for the activity	Mexico is in the top 10 world exporters of valuable resources for the activity
Access to the supply chain	15%	Mexico has explicit blockages or inabilities for the development of supply chains in this sector	Mexico has easy access to supply chains linked to the development of the production of this equipment
Talent & human resources	15%	Mexico has no human resources neither experiences in developing them for similar activities	Mexico is recognized worldwide for its knowledge on the field
Installed production capacity	10%	Mexico has no experience with this activity or related ones	Mexico already manufactures whole equipment or systems related to this sector
Manufacturing development ecosystem	20%	Mexico has unfavorable conditions for the development of an industry in the sector	Mexico has a fully established industry with continuous growth in the sector
National experience in developing new value chains	20%	Mexico has no experience with developing new value chains in the sector	Mexico has a huge and fresh experience with developing new value chains in related sectors
Trade context with potential consuming countries	10%	Mexican trade relationships with potential customers are damaged	Mexico has an active trade relationship with potential customers for the solution
Total	100%		

2.2. Electrolysers and Fuel Cells

2.2.1. Electrolyser and fuel cell technology

Electrolysers and Fuel Cells are electrochemical devices that use water and electricity to produce hydrogen and the opposite process, respectively. Electrolysers are the cornerstone of green hydrogen development, being the only economically viable method to produce zero-carbon hydrogen, as opposed to conventional steam methane reforming (SMR) or coal gasification, which are low cost but emission-intensive processes.

Electrolysers have water and electricity as inputs and use an electric current to split the H_2O molecule into hydrogen and oxygen, producing zero-carbon H_2. All electrolysers are made up by an anode and a cathode separated by an electrolyte, and the two main electrolyser technologies are alkaline (ALK) and Polymer Electrolyte Membrane (PEM).

ALK electrolysis is a mature technology with a high number of projects in operation and optimal for large-scale green H_2 production with constant or predictable demands, for example in the heavy industry sector. PEM electrolysis is a less mature technology with fewer projects in operation and optimal for projects with variable and unpredictable demands, restricted space, or supply H_2 simultaneously for more than one application, for example to provide grid stability services or on-site power to mobility projects.

Fuel cells use the chemical energy of the hydrogen to produce electricity, taking oxygen from the air and mixing it with hydrogen to generate an electric current, having only water and heat as by-products. They can provide power for a wide range of applications, being the most relevant power generation at different scales, including primary and back-up power, and for different modes of mobility from material handling within warehouses and factories to road transport in FCEVs or rail, maritime, and air transport.

Similar to electrolysers, fuel cells are made up of two electrode plates, an anode and a cathode, arrayed around an electrolyte membrane. Fuel cells have higher efficiencies than internal combustion engines and have no moving parts, making them silent and more reliable.

Finally, fuel cells are scalable and can be set together into fuel cell stacks for higher power capacities. The global fuel cell market is growing quickly as broader adoption takes place for stationary applications and, more importantly, the expected flourish of the FCEV market in the following years and decades.

2.2.2. Manufacturing potential of electrolysers and fuel cells in Mexico

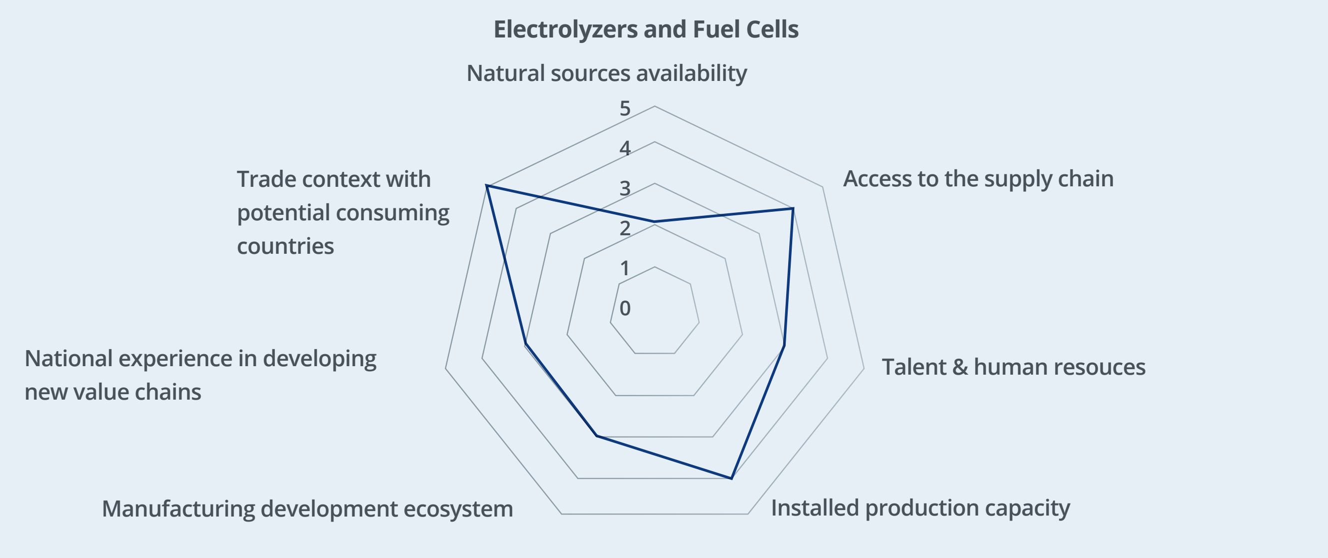
The results of the analysis for each dimension for electrolyser and fuel cell manufacturing are presented in the following table, briefly describing the argument behind the score for each dimension.

Table 2-2. Ratings for the manufacturing potential of electrolysers and fuel cells.

Criteria	Score	Argument
Natural resources availability	2	Even though Mexico is an important copper and steel manufacturer and has moderate graphite production, it does not have catalytic metals such as platinum or Iridium necessary for production.
Access to the supply chain	4	Mexico currently imports platinum and other metal catalysts for applications other than electrolysis.
Talent & human resources	3	In Mexico, prototypes of electrolysers and fuel cells have been developed on a small scale; however, there is no experience in scaling up these developments.
Installed production capacity	4	There is a small to medium manufacturing industry of chemical reactors and process equipment in Mexico. Metal-mechanical manufacturing parts are made in Mexico while measurement and instrumentation equipment is imported from the US, China and Europe.
Manufacturing development ecosystem	3	The chemical industry in Mexico only increased its contribution to GDP by 1% from 2012 to 2019. Another important indicator is the manufacturing industry, which grew from 15.9% of the GDP in 2007 to 17.3% of the GDP in 2017, showing a mild increase.
National experience in developing new value chains	3	The development of a new technological value chain in recent years has not been identified. Despite the recent discoveries of lithium mines in Mexico, the development of battery factories has not yet been seen. In the solar sector, the last inverter manufacturing plant was more than 10 years ago (Fronius - Monterrey).
Trade context with potential consuming countries	5	Mexico is a country with multiple free trade agreements. Among the countries with which Mexico has a signed agreement are Japan, European Union and Korea, all of them with ambitious goals for hydrogen adoption.
Weighted Rating	3.35	

Potential strengths are seen in access to the supply chain with existing imports, installed production capacity from metal-mechanical manufacturing, and favorable commercial relations having trade agreements with Germany, Japan, and Korea, i.e., large projected hydrogen markets. This gives Mexico a weighted rating of 3.35/5 in potential to manufacture fuel cells and electrolysers.

Figure 2-1. Radar chart with score for manufacturing potential for electrolysers and fuel cells in Mexico.



2.3. Conditioning and transport equipment

Conditioning and transport equipment include devices for hydrogen purification, compression, and transport. Hydrogen is produced as a gas usually at pressures of around 20-30 bar and needs to be compressed before transport, storage, or use. The most common pressures for hydrogen compression are 350 bar and 700 bar, being at 350 bar (H35) the standard for hydrogen refueling stations to supply fuel cell vehicles.

The majority of compressors currently used for gaseous hydrogen are either centrifugal compressors or positive displacement compressors. Centrifugal compressors work by rotating a turbine at high speeds to compress the H_2 gas and are the most widely used for pipeline applications given their high throughput, albeit providing a moderate compression ratio. Positive displacement reciprocating compressors drive a piston back and forth to compress the hydrogen gas and are the most widely used for applications that require high compression ratios.

As the name suggests, hydrogen purifiers remove impurities from the gas to provide high quality hydrogen for specific applications, such as use in PEM fuel cells or as required for specialized production processes as a reactant such as chemical vapor deposition to produce thin films for semiconductors. Different technologies are employed such as palladium membrane purification, dense thin-metal membrane purification, Pressure swing adsorption, catalytic recombination or deoxygenation purification, and electrochemical purification.

Hydrogen pipelines can be used to transport gaseous H_2 in the most cost-effective way for large volumes in a manner similar to the transport of natural gas. Some technical constraints are to be kept in mind to avoid gas leakage and material embrittlement when using conventional natural gas pipelines. Some proposed solutions include using fiber reinforced polymer (FRP) pipelines which are around 20% less costly than steel pipelines due to the easier manufacture of the polymer fiber pipe and reduced welding requirements.

2.3.1. Manufacturing potential of conditioning and transport equipment in Mexico

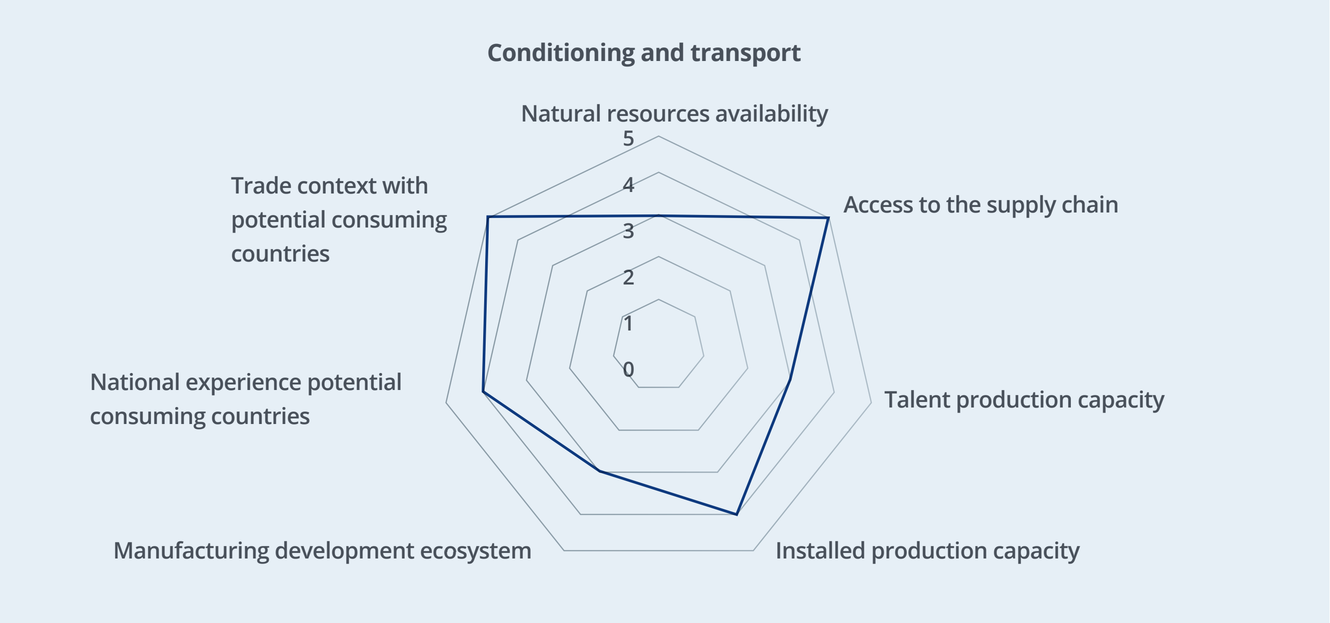
The results of the analysis for each dimension for conditioning and transport equipment manufacturing are presented in the following table, briefly describing the argument behind the score for each dimension.

Table 2-3. Ratings for the manufacturing potential of hydrogen conditioning and transport equipment.

Criterio	Puntaje	Argumento
Natural resources availability	3	Mexico has a good level of production of steel, coal and other elements associated with the manufacture of conditioning equipment (compressors, refrigerators, etc.) and transportation (tanks, containers, etc.)
Access to the supply chain	5	The industry of manufacturing compressors, valves, and ducts exists in Mexico. Although it is not specialized in hydrogen transport, it could migrate there very quickly.
Talent & human resources	3	Although the Mexican manufacture of equipment for the handling of special gases does not have the history of France, Germany or the United States, in Mexico there are personnel familiar with the manufacture and operation of this type of equipment.
Installed production capacity	4	Most of the Mexican equipment for conditioning and handling industrial gases is integrated with home-produced and imported goods.
Manufacturing development ecosystem	3	The equipment manufacturing industry in Mexico is growing at higher rates than the national economy, however no additional stimuli are identified for its growth
National experience in developing new value chains	4	The equipment manufacturing sector through metal-mechanical processes currently adopts new manufacturing and automation technologies.
Trade context with potential consuming countries	5	Mexico is a country with multiple free trade agreements. Among the countries with which Mexico has a signed agreement are Japan, European Union and Korea, all of them with ambitious goals for hydrogen adoption.
Weighted Rating	3.80	

Mexico already has an active manufacturing industry of compressors, valves, and ducts, being its experience and installed capacity important strengths, with remarkable access to the supply chains and trade context, resulting in a weighted rating of 3.80/5 for of hydrogen conditioning and transport equipment.

Figure 2-2. Radar chart with score for manufacturing potential for H_2 conditioning and transport equipment in Mexico.



2.4. Hydrogen storage

Hydrogen storage can be done in a wide range of time and volume scales, going from salt caverns for large-scale seasonal storage to pressurized tanks for uses as small as powering forklifts. Hydrogen is typically stored as a high-pressure compressed gas at 350 bar or 700 bar, and it is adequate for stationary use but also highly suitable for mobility applications given its high reliability, technical simplicity, energy efficiency and affordability.

Hydrogen is commonly stored in in carbon fiber composite tanks which are high-pressure compressed gas vessels with a high-density polymer liner to avoid gas leakage and are categorized as Type IV tanks to store hydrogen at 350 bar or 700 bar. These tanks have been mostly developed by FCEV manufacturers and have endured ballistic, drop, crash, and fire testing. The highest cost component of the Type IV H_2 tank corresponds to the carbon fiber composite, accounting for 60% of the cost of the storage system, as shown in Figure 3-3.

Figure 2-3. Cost breakout for a Type IV tank H_2 storage system.

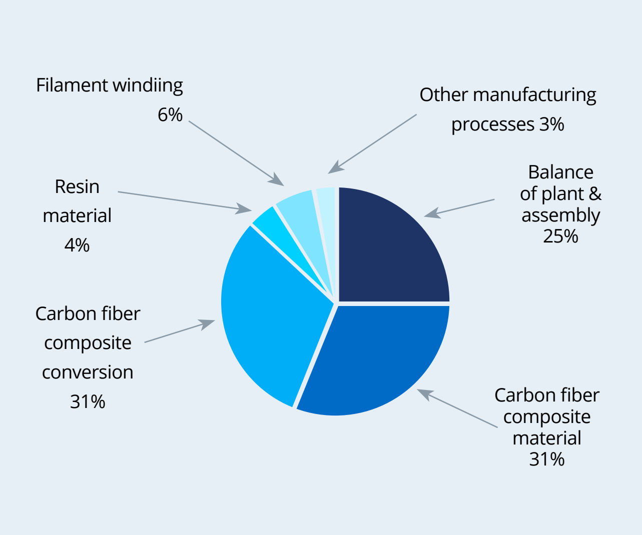


Table 2-4. Ratings for the manufacturing potential of hydrogen storage equipment.

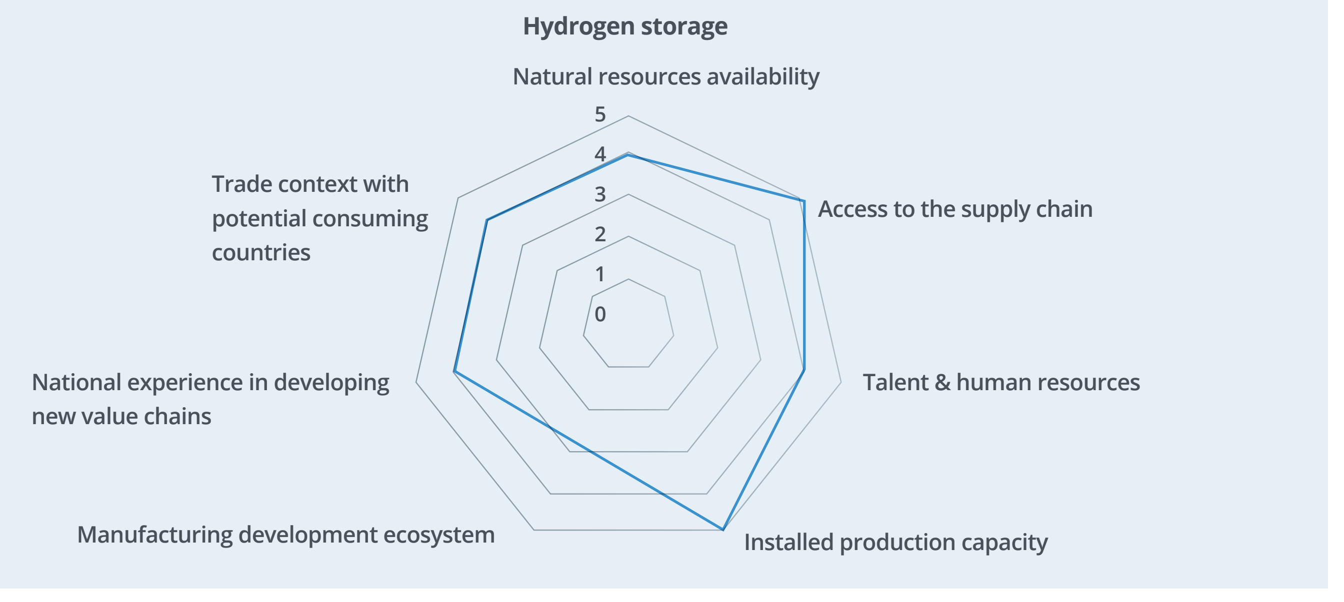
Criteria	Score	Argument
Natural resources availability	4	Mexico is the 15th largest steel producing country and the 6th largest carbon fiber producer in the world. This positions it as a relevant actor for the manufacture of hydrogen containers.
Access to the supply chain	5	Mexico currently produces steel containers and has access to the raw material to manufacture higher pressure containers (carbon fiber).
Talent & human resources	4	The manufacture of pressure tanks and adherence to ASME standards have maturity in Mexico. Human resources would only have to adapt this knowledge to the manufacture of composite tanks.
Installed production capacity	5	Mexico already has factories dedicated to the production of pressure tanks.
Manufacturing development ecosystem	3	Being considered a manufacturing activity, the manufacture of tanks has a Business as Usual growth in Mexico.
National experience in developing new value chains	4	The manufacture of pressure vessels currently belongs to the metal mechanical manufacturing sector. Both manufacturing techniques and compliance with standards are constantly changing.
Trade context with potential consuming countries	4	Mexico maintains good commercial relations with potential hydrogen tank consumers such as Germany, Japan and Korea, however they also have production capacities and potential for autonomy in this sector.
Weighted Rating	4.05	

2.4.1. Manufacturing potential of hydrogen storage in Mexico

The results of the analysis for each dimension for hydrogen storage manufacturing are presented in the table below, briefly describing the argument behind the score for each dimension.

Mexico is well-rounded for the production of hydrogen storage equipment, already producing high pressure storage tanks for other industrial gases. This gives the country strong scores among most criteria and an outstanding installed production capacity, resulting in a competitive weighted rating of 4.05/5 for hydrogen storage equipment.

Figure 2-4. Radar chart with score for manufacturing potential for hydrogen storage equipment in Mexico.



2.5. Power turbines

Power turbines that currently run on natural gas could introduce hydrogen to be partially combusted to generate power, reducing emissions compared to burning only natural gas and allowing to use existing infrastructure. Actually, hydrogen has been used in gas turbines for decades in refineries, petrochemical plants, and steel mills that produce hydrogen as a by-product along with other exhaust gases. Major gas turbine manufacturers are working on fuel flexible gas turbine combustion technology to introduce hydrogen with natural gas, currently allowing gas blends with hydrogen content as high as 30% and going a step further into developing turbines that run fully on hydrogen by 2030.

Some technical concerns are to be considered. Hydrogen's volumetric energy density is lower than that of natural gas (around 1/3), so the fuel system must be adjusted to make room for the increased flow necessary to compensate and deliver the same power rate. Additionally, hydrogen burns at higher temperatures and is more reactive than natural gas, posing additional challenges.

Hydrogen power turbines are expected to grow in demand globally to decarbonize the energy matrix, especially in countries where the hydrogen strategy considers them as a priority such as Japan and the US, which has planned close to 7 GW of hydrogen powered gas turbines to come online by 2030[1].

2.5.1. Manufacturing potential of power turbines in Mexico

The results of the analysis for each dimension for power turbine manufacturing are presented in the following table, briefly describing the argument behind the score for each dimension.

---

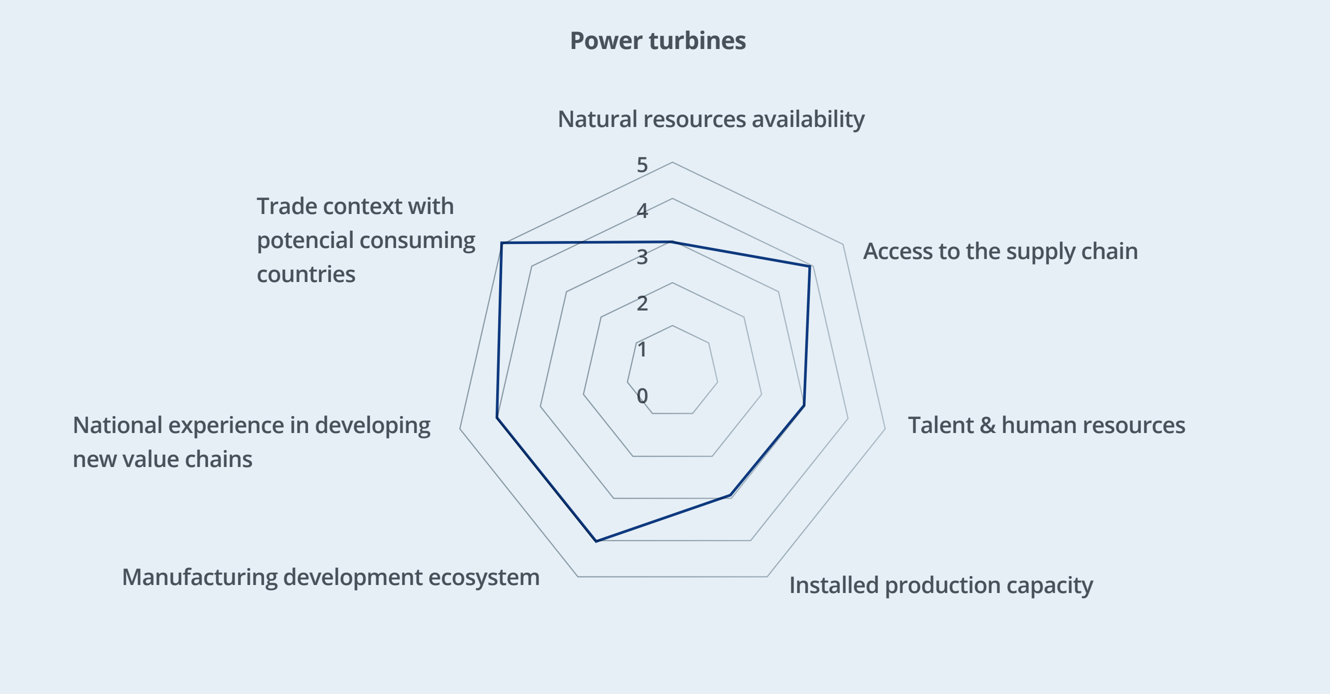
[1] BNEF, Hydrogen: The Economics of Power Generation, 2020.

Table 2-5. Ratings for the manufacturing potential of hydrogen power turbines.

Criteria	Score	Argument
Natural resources availability	3	Mexico has natural resources such as copper and steel for the manufacture of certain components, however it may require importing other resources for integrating high temperature materials and alloys.
Access to the supply chain	4	Since its growing participation in the aerospace sector, Mexico has access to supply chains for the manufacture of aeroderivative power generation turbines.
Talent & human resources	3	Mexico has experience in the operation and maintenance of combined cycle turbines (personnel from CFE, Siemens, GE, etc.) and some turbine manufacturing capabilities (mainly from the aerospace sector). However, it would be necessary to strengthen human resources for the production of this equipment.
Installed production capacity	3	Due to the country's participation in the aeronautical sector, it has experience in the manufacture of some components.
Manufacturing development ecosystem	4	There are no explicit plans for the manufacture of power generation turbines, however the aerospace industry is forecast to grow significantly. Production of power turbines could be a parallel growing industry.
National experience in developing new value chains	4	In addition to experience with the aerospace sector, in Mexico there are broadly developed capacities in the manufacture of electrical equipment such as transformers and power regulation equipment.
Trade context with potential consuming countries	5	Mexico has good commercial relations with countries that could demand hydrogen power turbines, such as the US. It also has good relationships with important companies such as General Electric and Siemens that could see Mexico with interest to produce this equipment.
Weighted Rating	3.75	

Mexico's experience, personnel, and infrastructure in the aerospace industry provides a foundation to further develop aeroderivative gas turbines and new, similar models that could be powered by hydrogen. However, there are talent and infrastructure capacity gaps to be bridged to make Mexico more competitive, resulting in a weighted rating of 3.75/5 for manufacturing hydrogen power turbines.

Figure 2-5. Radar chart with score for manufacturing potential for hydrogen power turbines in Mexico.



2.6.Fuel cell electric vehicles (FCEV)

Fuel cell electric vehicles (FCEV) store energy in the form of hydrogen, using it as an energy carrier, and employ it to generate electricity in a fuel cell, which in turn drives an electric powertrain to propel the vehicle. If fueled with green hydrogen, produced with the electrolysis of water using renewable electricity, they provide a zero-emissions transport alternative, having water as the only exhaust. This results in a tendency to compare FCEV with battery electric vehicles (BEV) as alternatives for the electrification and decarbonization of road transport.

This makes FCEVs especially competitive for long distance passenger transport, regional and national cargo logistics, and operations with intensive requirements, with the global fleet expected to grow rapidly, particularly in those segments.

Figure 2-6. Comparison of battery electric and fuel cell electric vehicles.

Battery electric Vehicles (BEV)

✗ Refuelling 40m - 8 h for 200 - 300 km

✓ Lower cost, higher efficiency

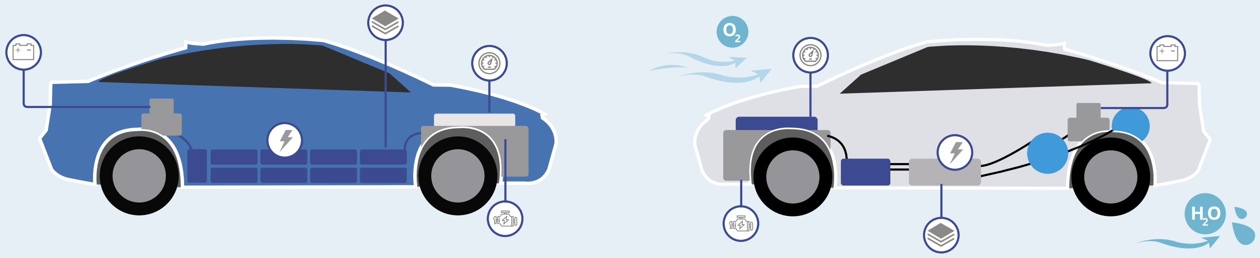
Better for:
- Light vehicles
- Short to medium distances
- Private use

Fuel cell vehicles (FCEV)

✓ Refuelling 4-6 minutes for 550 - 750 km

✗ Higher cost, lower efficiency

Better for:
- Freight and buses
- Long distances
- Intensive use (commercial)



2.6.1. Manufacturing potential of FCEVs in Mexico

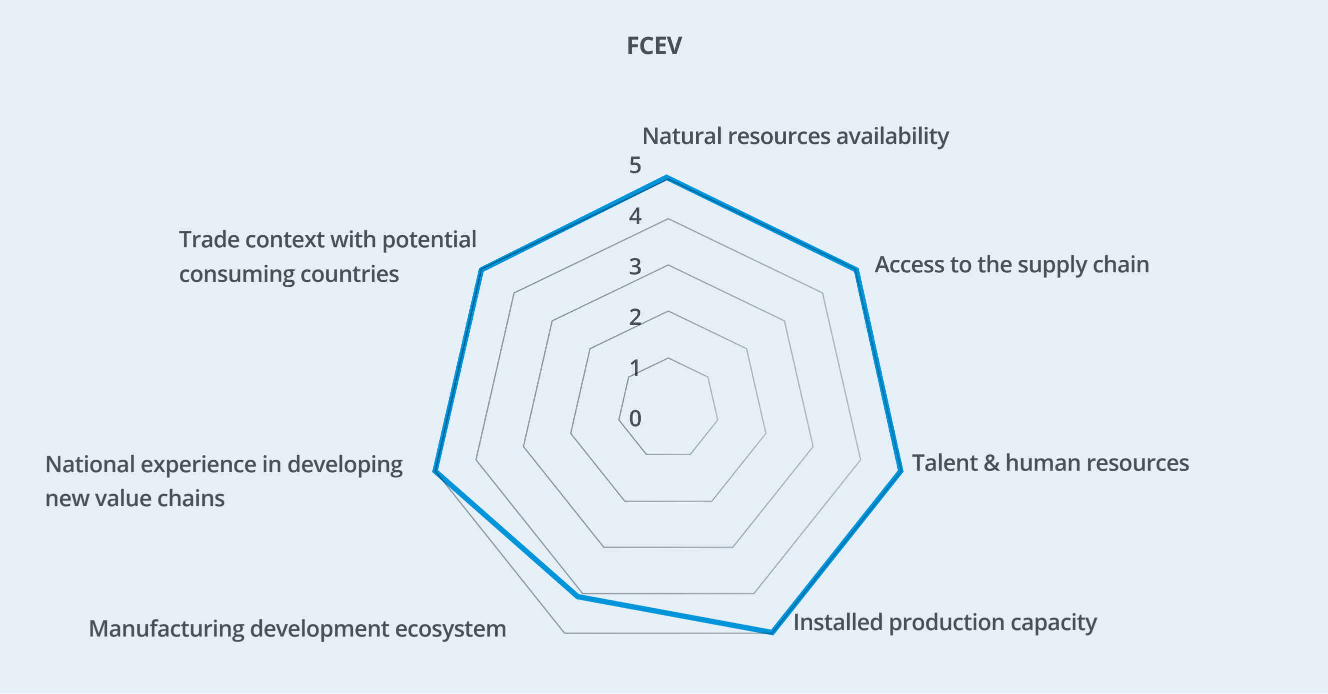
The results of the analysis for each dimension for fuel cell vehicle manufacturing are presented below, briefly describing the argument behind the score for each dimension. The manufacture of FCEVs in Mexico considers the assembly of the vehicles, not the production of all the components, integrating both nationally produced and imported parts according to their cost and supply.

Table 2-6. Ratings for the manufacturing potential of fuel cell electric vehicles.

Criteria	Score	Argument
Natural resources availability	5	Mexico is the fourth largest exporter of auto parts, of which more than 20% are completely metallic made.
Access to the supply chain	5	Mexico has full access to the supply chains of the automotive industry with the United States, Europe, and Asia.
Talent & human resources	5	1.8% of the economically active population works in the automotive sector.
Installed production capacity	5	Mexico has 26 plants in the automotive sector of 12 major automotive manufacturers, distributed in 15 states of the country.
Manufacturing development ecosystem	4	The automotive sector has an optimal development ecosystem in Mexico. During the last 5 years three new large plants have started operations in the country (BMW, Audi, and Toyota).
National experience in developing new value chains	5	Mexico has recent experience in installing/adapting electric vehicle assembly lines, with the Nissan Leaf plant in Aguascalientes and the recent announcement of that Ford's plant will produce the new Mustang Match-E in Estado de Mexico.
Trade context with potential consuming countries	5	Mexico is in the global top 10 of most activities within the automotive sector (exporter of vehicles, auto parts, engine producer, etc.), all of which are within the framework of international vehicle trade and specific trade agreements.
Weighted Rating	4.80	

Mexico's vast experience, capacity, skilled labor force, and renown as a manufacturer of cars and vehicle components leave it very well placed to establish FCEV manufacturing capacity, which is reflected in a weighted rating of 4.80/5.

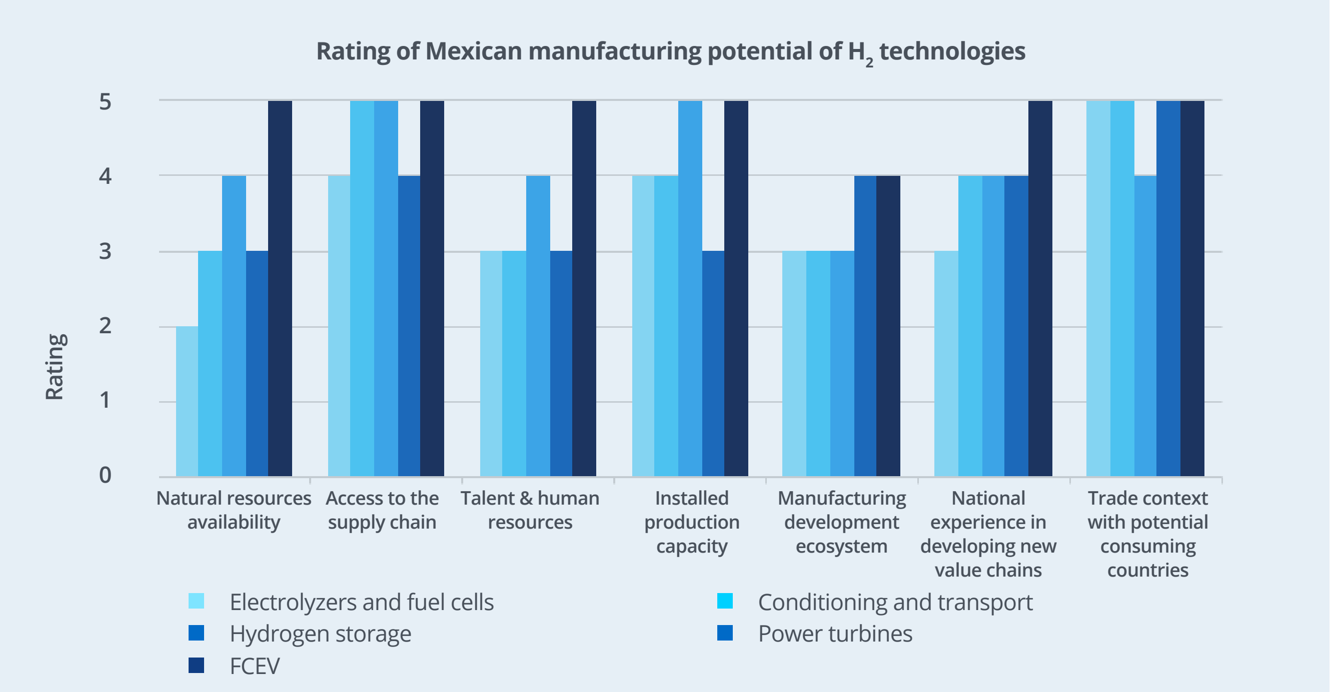
Figure 2-7. Radar chart with score for manufacturing potential for fuel cell electric vehicles in Mexico.



2.7. Ranking of manufacturing potential of hydrogen technologies

The metal-manufacturing, industrial gas components, aerospace, and automotive industries provide the basis for potential competitiveness to manufacture hydrogen technologies in Mexico. These settled industries provide the country with highly established value chains, manufacture infrastructure and experience, human resources, and an overall high degree of adaptability to adopt new industrial technologies and develop pioneering value chains and manufacturing ecosystems, as is reflected in the rating comparison for the studied technologies shown in Figure 2-8.

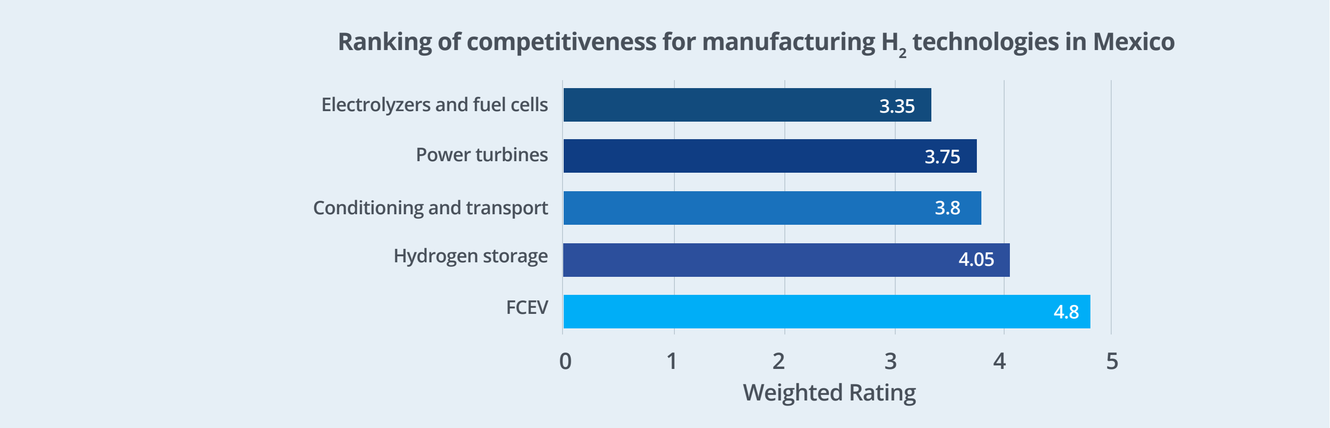
Figure 2-8. Rating comparison of manufacturing potential of hydrogen technologies by evaluation criteria.



The analysis shows Mexico as a country with potential to be competitive in the manufacture of hydrogen power turbines as well as conditioning, transport, and storage equipment, which will require the development of dedicated talent and strengthening the manufacturing ecosystems for related technologies into a hydrogen component and equipment producing market.

The automotive industry could continue to thrive in the country, leveraging on a robust manufacturing ecosystem to adopt new hydrogen FCEV technologies. When also considering a strategic location in North America and access to both the Atlantic and Pacific oceans, Mexico displays the potential to position itself as a leading manufacturer of FCEVs worldwide.

Figure 2-9. Ranking of competitiveness for the manufacture potential of hydrogen technologies in Mexico by weighted rating.



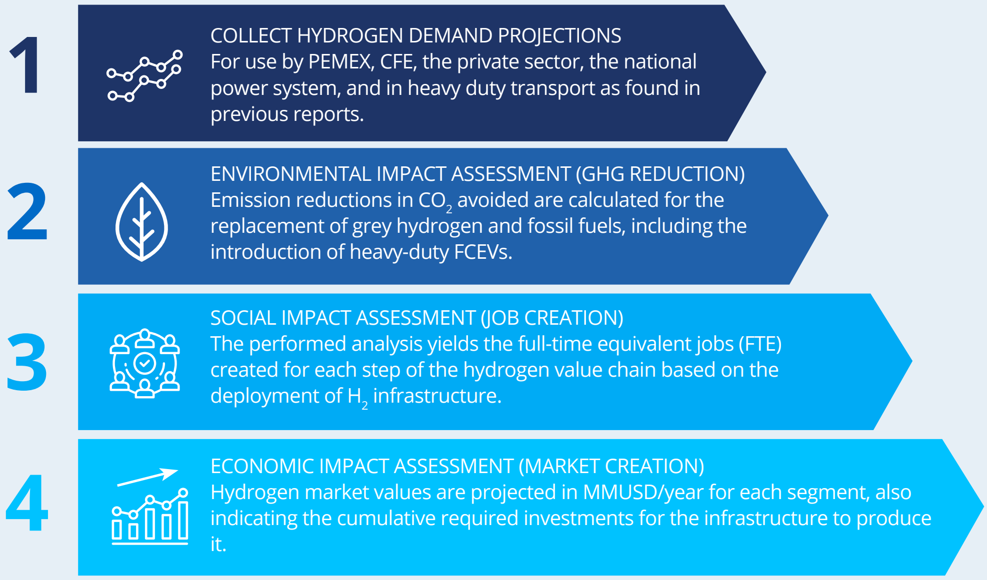
3. Social, environmental, and economic benefits of creating a green hydrogen value chain in Mexico

This section aims to quantify the social, environmental, and economic development impact that Mexico could have by developing a green hydrogen value chain following the findings on the previous reports of this series.

3.1. Methodology

A series of actions were followed to assess the impact across each dimension. The basis for these analyses are the green hydrogen demand projections made in volumes 2,3,4 and 5 of this series, which project green hydrogen demand in Mexico towards 2050 for a broad spectrum of applications including power generation, heavy duty road transport, injection into the gas network, production of synthetic fuels, mining, thermal energy in different industries, and use as a chemical feedstock for refining, production of ammonia and synthetic resins, among other.

Figure 3-1. Methodologic process of to quantify the environmental, social, and economic impacts of the green hydrogen demand in Mexico.



1 COLLECT HYDROGEN DEMAND PROJECTIONS
For use by PEMEX, CFE, the private sector, the national power system, and in heavy duty transport as found in previous reports.

2 ENVIRONMENTAL IMPACT ASSESSMENT (GHG REDUCTION)
Emission reductions in CO_2 avoided are calculated for the replacement of grey hydrogen and fossil fuels, including the introduction of heavy-duty FCEVs.

3 SOCIAL IMPACT ASSESSMENT (JOB CREATION)
The performed analysis yields the full-time equivalent jobs (FTE) created for each step of the hydrogen value chain based on the deployment of H_2 infrastructure.

4 ECONOMIC IMPACT ASSESSMENT (MARKET CREATION)
Hydrogen market values are projected in MMUSD/year for each segment, also indicating the cumulative required investments for the infrastructure to produce it.

- **Environmental impact:**

The potential for GHG emissions that could be avoided by switching to green hydrogen replacing conventional technologies such as fossil fuels or hydrogen from steam methane reforming, in tons of carbon dioxide equivalent ($tonCO_2e$) reduced.

- **Social impact:**

With the information obtained from the environmental impact and economic impact analysis, some social benefits that green hydrogen could bring to Mexico will be described, mainly focused on employment generation.

- **Economic impact:**

Through the LCOH calculations that were made for each H_2 application in previous reports a potential green hydrogen market size will be estimated for Mexico in 2030 and 2050 in millions of dollars per year.

The specific methodologies and assumptions for quantifying impacts in each are described accordingly.

3.2. Environmental Impact

The most notable environmental impact associated with green hydrogen is its lack of carbon emissions and having a very low climate footprint when produced, as its main inputs are renewable energy (mostly wind and solar PV) and water. The impact considered accounts for the reduction or avoidance of greenhouse gas (GHG) emissions, which include not only CO_2 and methane but also nitrous oxides, ozone, and other, and which are translated into a CO_2 equivalent corresponding to the amount of gas emitted times an emission factor relative to CO_2. This impact focuses not on the individual contribution of each gaseous component but rather on the overall carbon footprint as referenced from various sources mentioned bellow.

To perform this assessment, the end uses are divided into two categories depending on the use of green hydrogen: (1) replacement of gray hydrogen and (2) replacement of fossil fuels. The latter category can be further divided to create a new one for (3) road transport. This allows for a straightforward quantification o the emissions reduced.

3.2.1. GHG reduction from replacement of gray hydrogen

The end-uses analyzed where electrolytic hydrogen directly replaces hydrogen produced from natural gas are: as feedstock for refineries and production of ammonia (mainly for fertilizers), float glass, synthetic resins, food fats, and other uses within the chemical industry. Over 98% of the projected green hydrogen demand and the associated emission reduction by replacing gray hydrogen are in refining and ammonia production, activities performed by PEMEX in Mexico, which will be the focus of this analysis.

The production of hydrogen by steam methane reforming (SMR) has a carbon equivalent GHG intensity of 9.26 $kgCO_2e/kgH_2$, according to research from the Argonne National Laboratory[2] in the US which considers emissions from both the combustion and chemical conversion within the hydrogen production process.

Green hydrogen can have variable carbon neutrality levels depending on the emissions reduced in its production relative to the conventional method, which can range from 60%, which the minimum required by CertifHy[3] to be considered green hydrogen, to 100% when produced with electrolysis supplied entirely by zero-carbon renewable energy sources.

To explore the maximum potential of emissions reduction zero-carbon green hydrogen will be considered. GHG reductions with different carbon neutrality levels would be proportional to the level of neutrality considered.

The CO_2 avoided by the introduction of green hydrogen in refineries and ammonia production in Mexico would surpass 180 thousand $tonCO_2e$/year by 2030 and reach more than 3.2 million $tonCO_2e$/year by 2050, as shown in Figure 4-2 and Figure 4-3.

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[2] Argonne National Laboratory, Updates of Hydrogen Production from SMR Process in GREET 2019.

[3] CertifHy is the first and EU-wide acknowledged guarantee of origin certification for green hydrogen, developed by a consortium led by Hinicio.

Figure 3-2. Projected GHG emissions avoided by the replacement of gray hydrogen with green hydrogen.

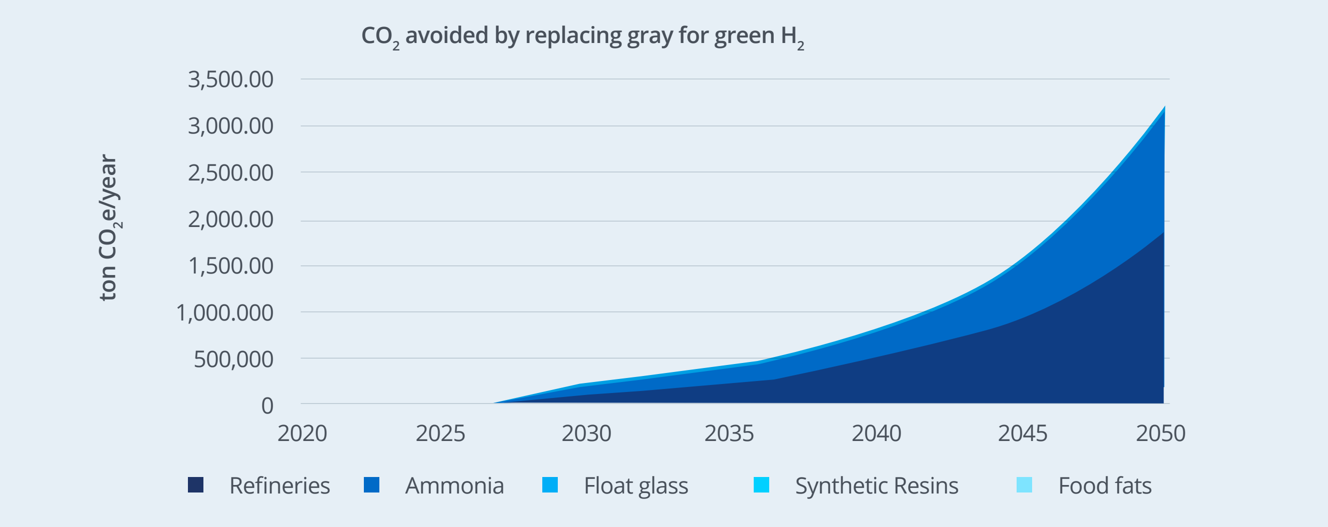
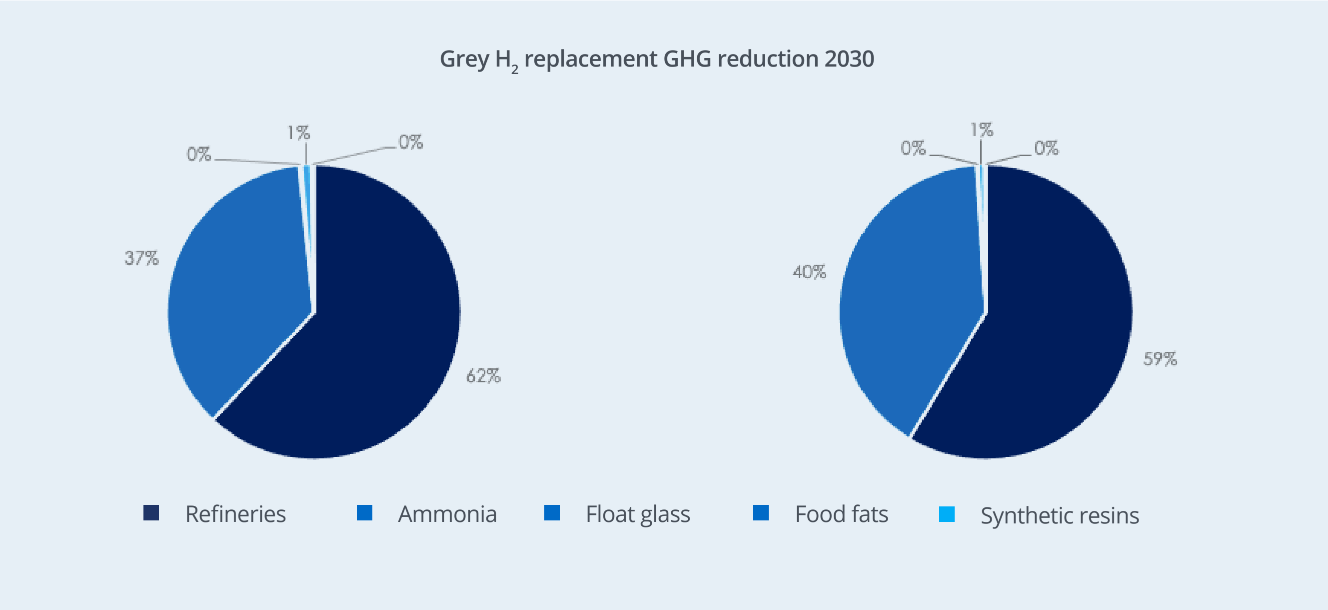


Figure 3-3. Gray H_2 replacement contribution to GHG mitigation by sector in 2030 and 2050.



3.2.2. GHG reduction from replacement of fossil fuels

Green hydrogen can replace fossil fuels in applications such as power generation, industry, and mobility. Mobility will be assessed in the following section to focus in this one on power and industry applications.

Green hydrogen can replace natural gas in power turbines, when injected in the gas network, and in thermal applications for industries such as cement and mining. In all these end-uses, hydrogen supplies the energy content of the natural gas it substitutes, and the GHG emissions reduction can be accounted by the change in carbon intensity of the energy demand, expressed in MMBTU (common in the natural gas market), or by the amount of hydrogen required in kg. Natural gas has a GHG intensity of 61.6 kg CO_2e/MMBTU, as found in data from Veolia for the City of Winnipeg[4], which could be avoided entirely by combusting carbon neutral green hydrogen instead.

Natural gas is also used as a chemical reactant in mineral ore reduction, and the introduction of green hydrogen could reduce its impact of 2.86 kgCO_2e/kgNG for the natural gas or reactively equivalent reducing gas used.

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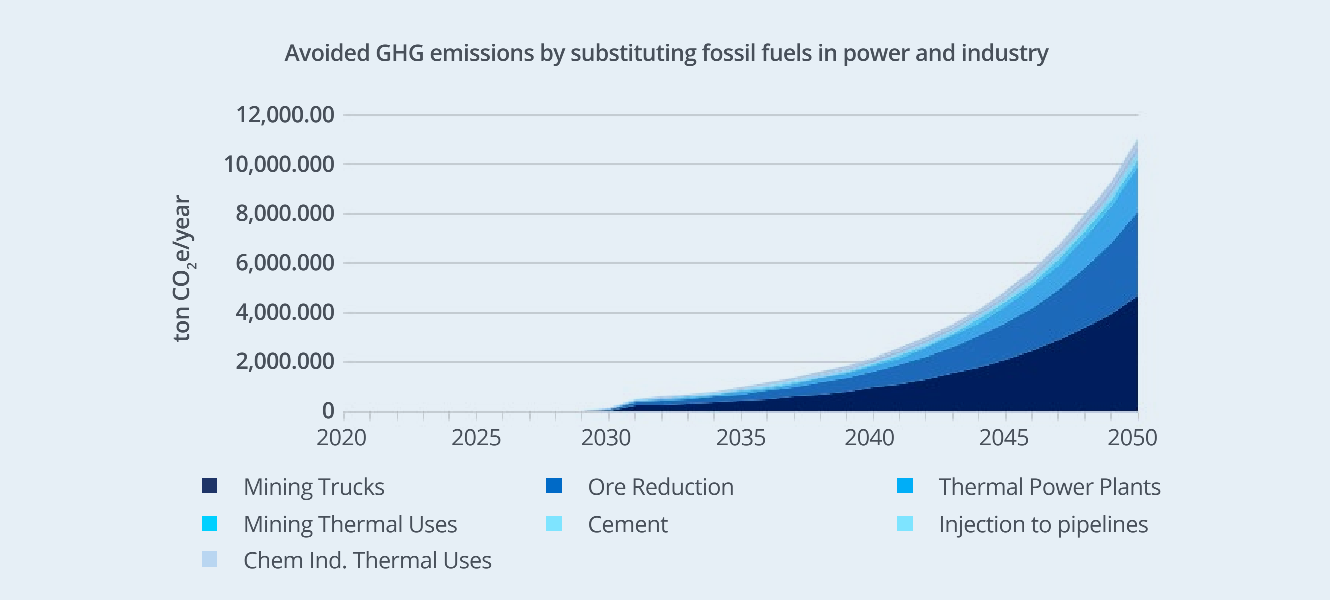
[4] Veolia, Winnipeg Sewage Treatment Program Report, 2012.

Figure 3-4. Projected GHG emissions avoided by the replacement of fossil fuels with green hydrogen in power generation and industry.

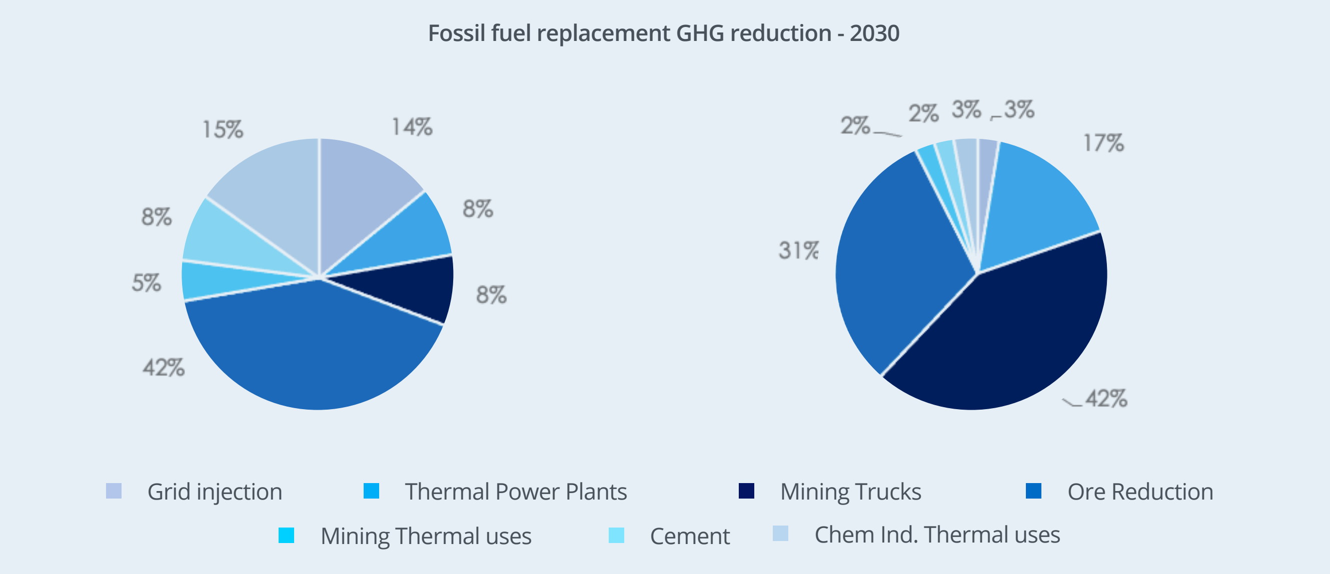


For mining trucks, a report from the Chilean Production Development Corporation (CORFO) estimated the emissions for every mining truck or CAEX[5] to be of 3,100 tonCO$_2$/CAEX·year. The report on hydrogen opportunities for the private sector estimated the fleet size of hydrogen FC CAEX in the country, which reaches 1,500 units by 2050.

The largest GHG reduction potential towards mid-century can be observed in the mining and metals industry accounting for three-quarters of the CO$_2$ avoidance potential. Introducing fuel cell mining trucks could reduce 4.6 million tonCO$_2$e/year by 2050 and introducing green hydrogen into iron ore reduction could contribute with 3.3 tonCO$_2$e/year.

Burning hydrogen in thermal power plants could be the second largest area of GHG avoidance with up to 1.9 million tonCO$_2$e/year by 2050. Injecting hydrogen into the gas network and using it in cement production and thermal applications in the chemical industry would jointly reduce 0.84 million tonCO$_2$e/year.

Figure 3-5. Fossil fuel replacement contribution to GHG mitigation in power generation, thermal applications, and industry in 2030 and 2050.



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[5] CAEX: mining haul truck, from Spanish Camiones de Extracción.

Replacing fossil fuels with green hydrogen for applications in power generation and industry has the potential of reducing up to 7.6 million tonCO_2e/year in 2050, with around three-quarters of the reduction coming from the mining and metals industry, mostly mining trucks, and under one fifth to power generation in hydrogen turbines.

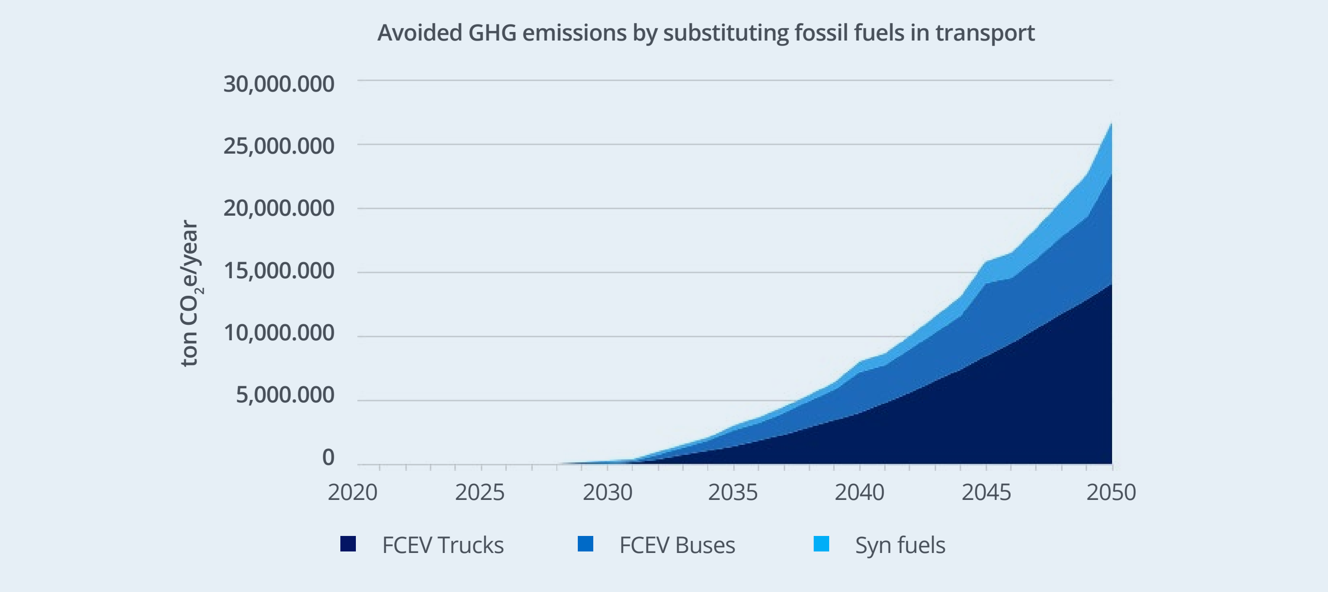
3.2.3. GHG reductions in road transport

Hydrogen replaces fossil fuels in road transport mainly through two routes: powering hydrogen FCEVs for heavy duty road transport and in synthetic fuels. The heavy-duty vehicles (HDVs) considered are divided into public transport buses and long-distance freight trucks.

FCEVs are electric vehicles which store hydrogen as an energy carrier and use it to generate electricity in a fuel cell, which in turn supplies an electric powertrain. Given their long range, quick refueling times, and low capacity loss by weight and volume relative to conventional internal combustion engine vehicles (ICEVs), they are projected to be highly competitive in heavy duty applications, surpassing battery electric vehicles (BEVs) in performance and both ICEVs and BEVs in cost per unit owned around 2030.

To calculate the GHG emissions avoidance from heavy duty FCEVs the hydrogen demand projections from the previous report on hydrogen opportunities in the transport sector is considered for both public transport buses and heavy-duty freight trucks towards 2050, as well as the projected FCEV fleet for these segments. The projected CO_2 avoidance can then be obtained using the evolving efficiencies of FCEVs and the GHG intensity following current and expected emissions standards. For this purpose the European Emission Standards[6] for buses and trucks are considered as follows: Euro IV (the current standard in Mexico, released in 2005) for the ongoing 2020's decade and the stricter Euro V (published in 2008) and Euro VI (dated 2012) for the 2030's and 2040's decade, respectively, which each set emissions limits for buses and HDVs. Following such standards considers an average carbon intensity of 967 gCO_2e/km·vehicle for buses and 679 gCO_2e/km·vehicle for trucks in 2021-2050.

Figure 3-6. Projected GHG emissions avoided by the replacement of fossil fuels with green hydrogen in transport.



Synthetic fuels (syn-fuels) are the second pathway considered for using hydrogen to substitute fossil fuels in mobility. They are produced combining green hydrogen (H_2) with capture CO_2 to generate synthetic hydrocarbons, which are identical in composition to their conventional fossil counterparts but with net-zero carbon emissions. Once deployed, they could be readily used in vehicles than run on conventional gasoline, diesel, or other hydrocarbon fuels. Every liter of diesel substituted with syn-fuels avoids the emission of 2.79 kgCO_2e/L.

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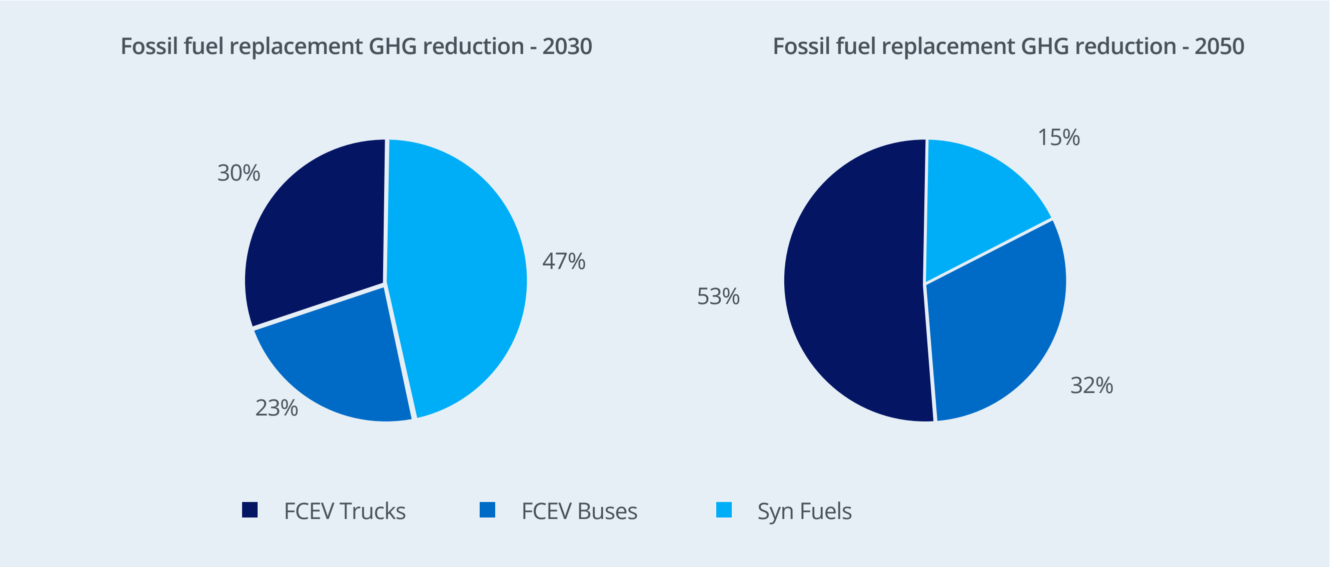
[6] European Commission, Commission Regulation (EU) No 582/2011.

Figure 3-7. Fossil fuel replacement contribution to GHG mitigation in transport in 2030 and 2050.



Replacing ICEVs with FCEVs and fossil with synthetic fuels could avoid the emission of 280 thousand tonCO$_2$e/year in 2030, of which nearly half would correspond to the use of synthetic fuels. However, a broad deployment of heavy-duty FCEVs is expected to accelerate after 2030 as they reach cost parity with ICEVs and BEVs, further growing their demand and the associated carbon footprint.

By 2050, substituting ICEVs with FCEVs and diesel with syn-fuels could reduce GHG emissions by up to 26.7 tonCO$_2$e/year, of which around half would come from FCEV trucks, one third from FCEV buses, and 15% from synthetic fuel use.

3.3. Social Impact

The social impacts of the introduction and growth of green hydrogen infrastructure and solutions in Mexico could have a variety of angles from which to be studied. However, this report focuses on the creation of jobs associated with the creation and growth of the hydrogen economy in Mexico.

This analysis gathers existing research which estimates job creation with the development of hydrogen projects from sources such as Navigant Consulting[7], Element Energy[8], and CE Delft[9]. This analysis yields the full-time equivalent jobs (FTE) created for each step of the hydrogen value chain, including construction and installation of infrastructure, operation and maintenance (O&M) of equipment, electrolyzer and fuel cell manufacturing, and the deployment and maintenance of the hydrogen FCEV fleet and the required refueling infrastructure.

A given number of full-time equivalent (FTE) jobs are allocated to each step of the hydrogen value chain, divided into direct and indirect jobs created by the installed capacity of electrolysis for the deployment and maintenance of green hydrogen production infrastructure, and of jobs per million of dollars invested in hydrogen refueling infrastructure for road vehicles. The results of this analysis are shown in the following tables.

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[7] Navigant, Gas for Climate – Job creation by scaling up renewable gas in Europe. 2019.

[8] Element Energy. Hy-Impact Series: Hydrogen for economic growth, 2019.

[9] CE Delft, Green hydrogen and employment, 2019.

Table 3-1. Jobs created in the green hydrogen production infrastructure in Mexico.

Hydrogen Production	Jobs in 2030	Jobs in 2050
Construction and Installation	765	34,701
Jobs associated with Machinery and Equipment	438	19,849
Jobs associated with Electrical Materials	67	3,054
Jobs associated with Construction and Civil Works	67	3,054
Jobs associated with other technical services	34	1,527
Jobs associated with R&D services	34	1,527
Jobs associated with non-technical services	34	1,527
Jobs associated with Machinery and Equipment	18	833
Jobs associated with Pipeline	50	2,290
Jobs associated with Construction and Civil Works	9	416
Jobs associated with other technical services	9	416
Jobs associated with non-technical services	5	208
O&M	356	16,154
Jobs associated with O&M - energy services	177	8,012
Jobs associated with equipment replacement	44	2,003
Jobs associated with O&M - energy services	27	1,228
Jobs associated with O&M - pipeline transport	7	307
Jobs associated with energy costs	88	3,990
Jobs associated with equipment replacement	14	614
National Manufacture of Electrolysers	475	7,739
Jobs in manufacture of equipment for national use	475	7,739
Jobs in manufacturing of equipment for export	0	0
Total	1,596	58,594

Table 3-2. Jobs created in the manufacture of FCEVs in Mexico.

FCEVs – Automotive Industry	Jobs in 2030	Jobs in2050
Direct Income-created Jobs - Automotive Industry	125	9,268
Indirect Income-created Jobs - Automotive Industry	60	4,512
Total	186	13,780

Table 3-3. Jobs created in construction and maintenance of HRS in Mexico.

Hydrogen Refueling Stations (HRS)	Jobs in 2030	Jobs in 2050
Direct Jobs HRS	90	4,580
Jobs associated with HRS Construction and Installation	5	253
HRS O&M partner Jobs	85	4,327
Indirect Jobs HRS	273	13,859
Jobs associated with HRS Construction and Installation	82	4,185
HRS O&M partner Jobs	191	9,674
Total	363	18,439

Over 90,000 people could be employed by the green hydrogen economy in Mexico in 2050. The largest area of job creation in Mexico is in the production of green hydrogen itself and the required infrastructure, which is projected to employ nearly 1,600 people by 2030 and close to 58,600 workers by 2050. These jobs are split into the construction and installation stage operation and maintenance (O&M), and the manufacture of electrolysers. Construction and installation consider employment in the manufacture and supply of machinery and equipment, electrical materials, construction and civil works, R&D services, and other associated technical services and non-technical services. Jobs in O&M for hydrogen production infrastructure include energy costs and services, equipment replacement, hydrogen transport, and jobs associated with equipment replacement such as tubes, valves, and storage tanks.

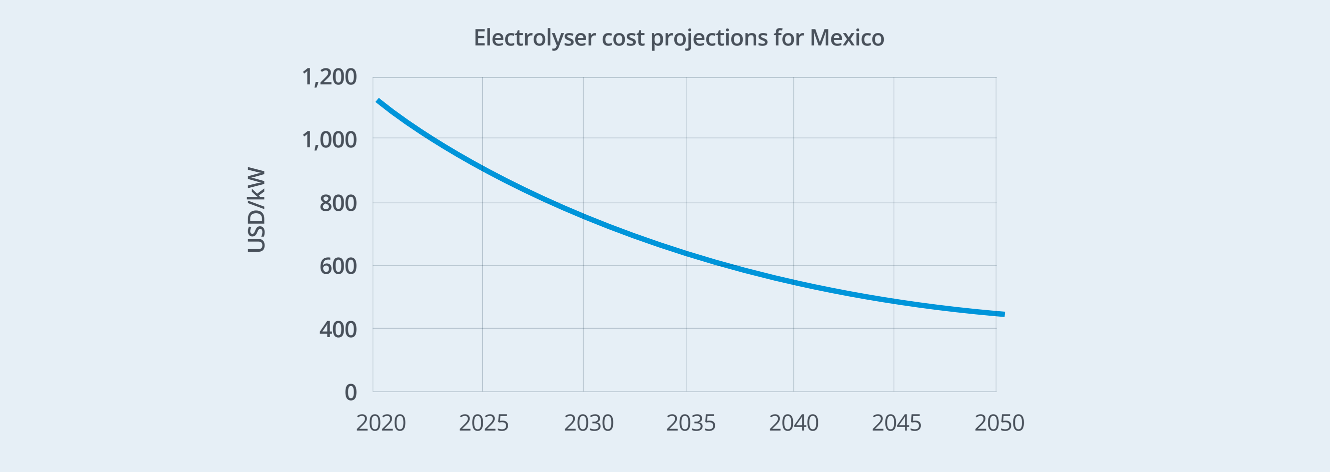
The second largest area of employment is projected to be in the hydrogen refueling infrastructure, hiring over 360 people in 2030 and growing to 18,400 by 2050, of which around three quarters area indirect jobs. Finally, the automotive industry would have hired under 200 workers in 2030 but grow to employ nearly 13,800 workers by mid-century, of which around two-thirds would be directly employed in the manufacture of FCEVs.

3.4. Economic Impact

The economic impact of the development of a green hydrogen economy in Mexico can be quantified by the size of the markets it is projected to create across the different segments and applications, as well as the investments required in hydrogen infrastructure to meet the demand. In the previous reports hydrogen demand projections were made for different end-uses in Mexico up to 2050, which can be related to the H_2 market size at a given year and provide a quantified measure using the projected Levelized Cost of Hydrogen (LCOH). It must be noted that additional price components must be considered such as the costs of hydrogen transport, storage, and supply at refueling stations, where applicable, costs which vary depending on location, taxes and tariffs, and utility margins for the various steps within the hydrogen production and supply value chain.

The second measure for economic impact considered are the investments that hydrogen infrastructure will bring to the country, in particular the capital expenditures in the hydrogen production plants. This includes all investments necessary to set up the electrolysis facilities, such as those attributed to the electrolyser stacks, procurement and construction, balance of plant, among other. A model of Hinicio which projects the total installed cost per MW of electrolysis capacity was used, which projects the cost reduction of electrolysers starting at over 1,000 USD/kWEz in 2021 and dropping to nearly one third of that value by 2050, as shown in Figure 4-8.

Figure 3-8. Installed electrolysis costs projections in Mexico.



The economic impact is divided into three segments following the structure of the previous reports, namely for activities related to the state-owned companies, the second with focus on the private industrial sectors, and the third on heavy duty road transport.

The first one is focused on activities related to the state-owned energy companies PEMEX and CFE. They consider hydrogen use in refineries, ammonia production, and synthetic fuels[10] for PEMEX, and injection of hydrogen in natural gas infrastructure and power generation in turbines fueled with a mix of hydrogen and natural gas for CFE. These segments represent the largest concentrated market values among hydrogen uses in terms of market size per player given the size of both companies' operations, with a joint expected impact of roughly 100 million USD per year by 2030 and growing to more than 1.3 billion USD yearly 2050 to supply hydrogen to PEMEX and CFE.

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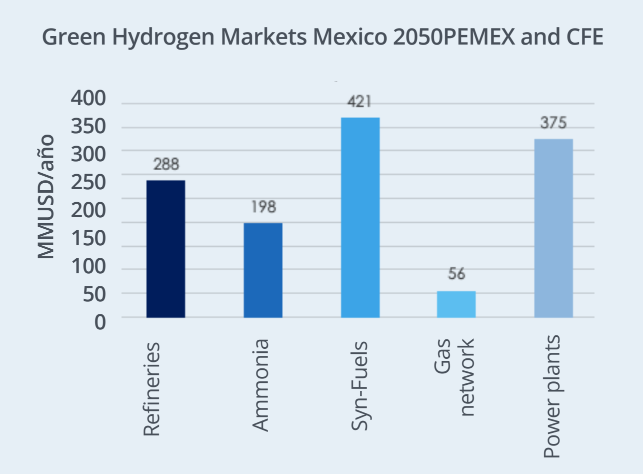
[10] Synthetic fuels are hydrocarbons artificially produced by synthesizing green H2 with captured CO2. They have the same chemical composition as their fossil counterparts and carbon neutral.

For PEMEX the most notable impact by mid-century is projected in the production of synthetic fuels, with a hydrogen market value of 420 MMUSD/year, followed by hydrogen use in refineries with close to 290 MMUSD/year, and finally ammonia production with 200 MUSD/year. Considering that the production of synthetic fuels could also be done by private actors, the economic impact left for activities currently pursued only by PEMEX would have an economic impact of close to half a billion dollars per year by 2050.

For CFE the largest economic impact is projected to be in the production of electricity in turbines powered by hydrogen and natural gas. The production of hydrogen for this purpose alone would have a value of 375 MMUSD/year by 2050, whereas injection in the gas network represents a smaller opportunity due to lower economic competitiveness, valued at 56 MMUSD/year and similar to the impact expected in other segments such as the cement and chemical industries. All these hydrogen uses for state-owned companies would create new markets, jobs, and opportunities for economic development.

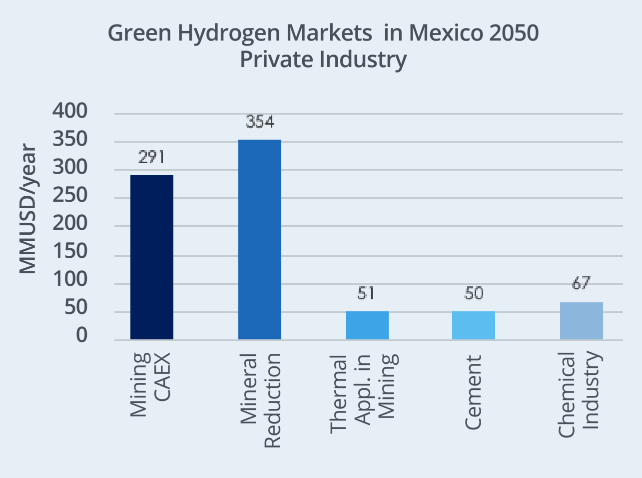
Figure 3-9. Hydrogen market value by 2050 for segments most pertinent to PEMEX and CFE.



The second segment focuses in hydrogen opportunities for the private industry and includes the mining and metals, cement, and chemical industries. For mining, the impact is split into powering fuel cell mining haul trucks or CAEX (Camiones de Extracción), the chemical reduction of metallic ores, and thermal applications. For the cement and chemical industries both market sizes and investments are determined encompassing all projected applications of hydrogen.

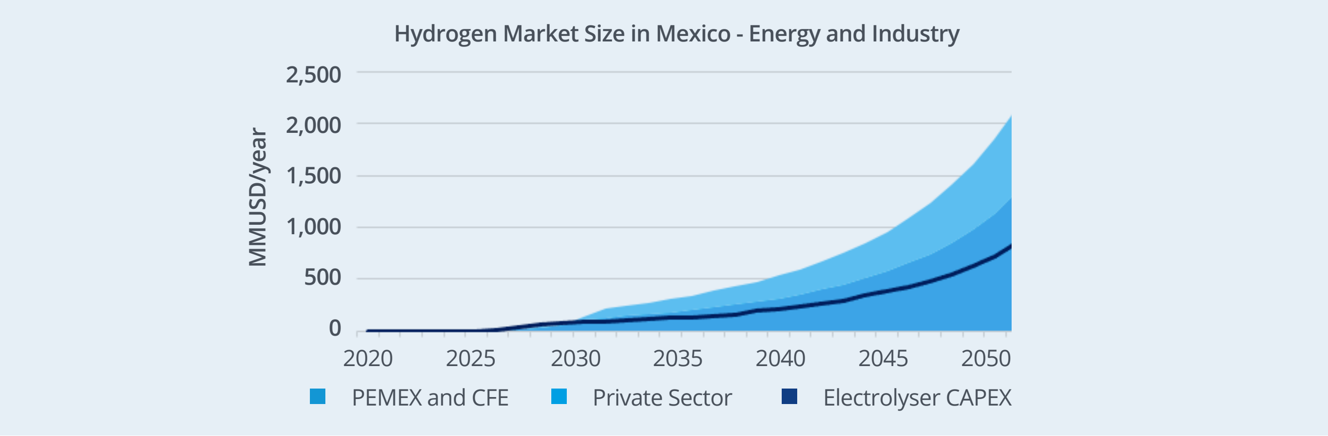
The largest projected opportunities in hydrogen for the private industries are in FC CAEX and mineral ore reduction, which jointly account for nearly 80% of the economic impact. Projections show a hydrogen market size by 2050 of around 300 MMUSD/ year for fueling H_2 mining trucks, 350 MMUSD/year for mineral ore reduction, mainly iron ore for steel production, 50 MMUSD/year for thermal applications in the mining sector, and close to 120 MMUSD/year for the cement and chemical industries combined, adding up to 800 MMUSD/year for private industry uses.

Figure 3-10. Hydrogen market value by 2050 for the private industrial segments.



All industrial and energy segments in Mexico will have a growing economic impact which reaches a hydrogen market of 200 MMUSD/year by 2030 and takes off to grow more than tenfold and surpass 2 billion USD/year by 2050. Investments in hydrogen producing infrastructure grow along the hydrogen demand. Cumulative investments for supplying hydrogen to PEMEX and CFE are projected in close to 4.3 billion by mid-century, and in nearly 2.6 billion to supply the private industry.

Figure 3-11. Hydrogen market size projections for energy and industrial uses.



Thirdly, the heavy-duty road transport presents the largest economic opportunities for hydrogen in Mexico. Split into public transport buses and long-haul trucks, they represent a hydrogen market that will begin broad deployment after 2030 but will accelerate quickly to be valued at 2.6 billion USD/year by 2040 and reach 6 billion USD/year by 2050, split into 2 billion for public transport buses and 4 billion for freight trucks per year. These values consider an average price at which hydrogen could be sold at Hydrogen Refueling Stations (HRS) across the country, which considers a 2.5x increase in the cost of hydrogen relative to production attributed to hydrogen conditioning, transport, storage and supply.

Furthermore, these values represent only the market of the hydrogen supplied and large economic impacts can also be expected from the deployment and operation of hydrogen refueling infrastructure and, moreover, the automotive industry's sales and maintenance of the heavy-duty FCEVs, which are projected to grow to a fleet of nearly half a quarter million public transport buses and another quarter million for long-haul trucks powered by hydrogen.

Cumulative investments of nearly 8.5 billion USD by 2050 are projected to supply the hydrogen demand for heavy-duty FCEVs in Mexico.

Figure 3-12. Hydrogen market value by 2050 for heavy-duty road transport.

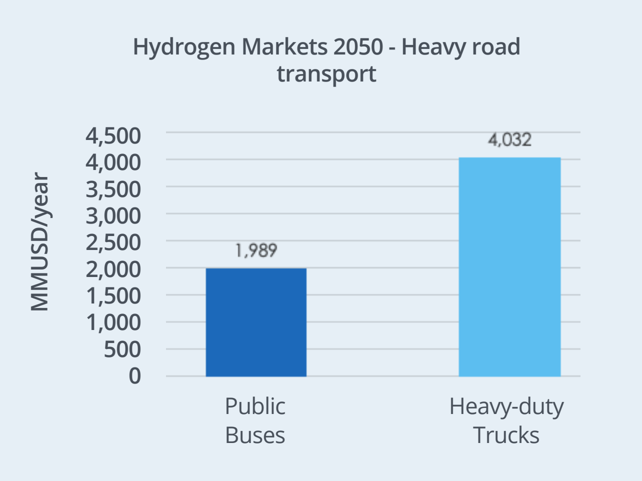
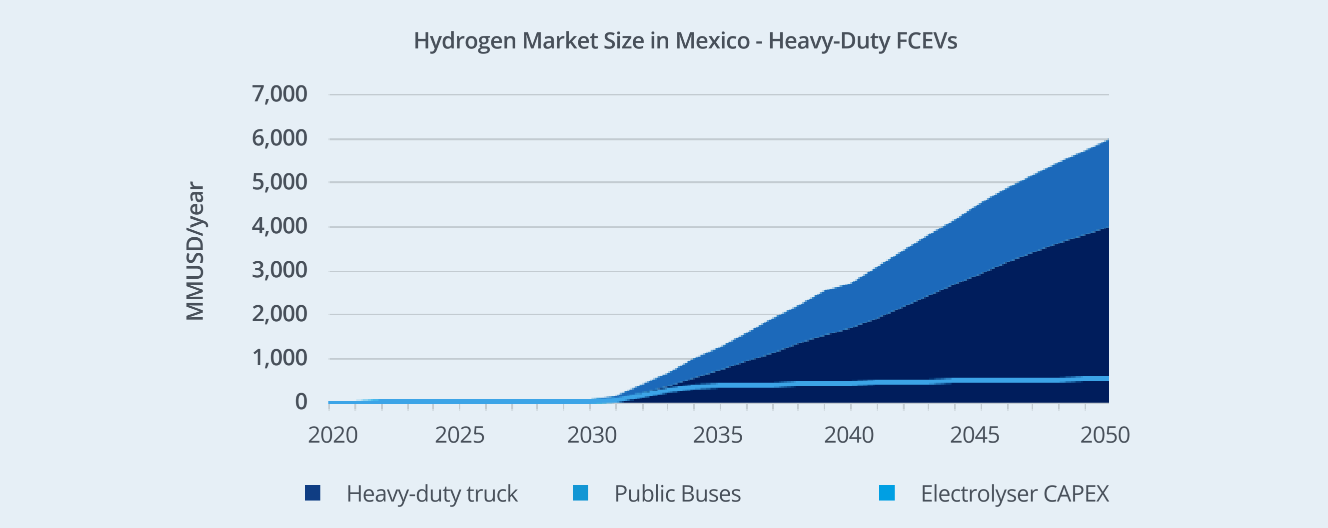


Figure 3-13. Hydrogen market size projections for heavy-duty road transport.



4. Regulatory and financial recommendations to enhance hydrogen production in Mexico

The development of the green hydrogen economy faces challenges from the technical, economic, regulatory, and financial perspectives. Given the cost of green hydrogen relative to gray and the conventional fossil-based alternatives it is set to replace, both financial and regulatory incentives and enabling measures are needed to help it achieve cost competitiveness and be more attractive, both to producers and for adoption by end-users. Without incentives, the consumption of fossil fuels would spread at a lower economic cost, but with important environmental repercussions.

Similarly, green hydrogen faces regulatory and financial challenges to be overcome for a timely and broad deployment in Mexico. This study intends to identify and emit recommendations on how to address these challenges. In particular, this chapter will present a collection of barriers for green hydrogen in Mexico identified throughout the development of the previous volumes from this series which focus on opportunities for state-owned and private companies in energy, industry, and mobility.

Additional barriers and inputs for recommendations are gathered from interviews with relevant actors in Mexico in late 2020 and early 2021. The recommendations issued for each barrier are based on the deployment of other energy technologies in the past in Mexico, the current adoption of hydrogen in other regions and international references, or a combination of both.

The barriers and recommendations for the deployment of green hydrogen in Mexico are grouped into Policies and Regulation, Economic and Political Context, Technology and Human Capital, and are described along with their impact, recommendations to address them and expected benefits of implementing them. Finally, a set of recommendations based on International Experiences are also presented.

The nine barriers identified are the following:

Policies and Regulation

1. Mexico’s current public policy and regulatory framework can be strengthened to meet its international climate commitments.
2. As in most countries, there are no national or state policies or roadmaps for the development of hydrogen in Mexico.
3. The regulation for the use of hydrogen in Mexico is unspecific for most of its possible applications.

Economic and Political Context

4. Mexico’s access to low-cost natural gas from the U.S. poses challenges in green hydrogen’s competitiveness.
5. In Mexico, access to energy infrastructure presents significant entry barriers for new renewable energy-derived projects.
6. The geographic availability of renewable energy generation plants in Mexico does not necessarily match with the most suitable hydrogen demand for the deployment of large-scale green hydrogen projects.
7. There is a wide cost-competitiveness gap between green hydrogen production and consumption technologies compared to conventional alternatives.

Technology and Human Capital

8. Barriers of knowledge about the uses of hydrogen and its potential impacts.
9. Limited or unlinked human resources from the energy sector trained in green hydrogen.

4.1. Policies and Regulation

1. Mexico's current public policy and regulatory framework can be strengthened to meet its international climate commitments.

- **Recommendations:**

a) By including green hydrogen in policies regarding climate change, Mexico would have an additional vehicle to achieve its climate goals and increase the ambition of their mitigation actions.

Benefits: The economy of hydrogen could represent an opportunity to strengthen industrial policy, by developing technologies locally.

2. As in most countries, there are no national or state policies or roadmaps for the development of hydrogen in Mexico.

- **Impact:** In Mexico, interest in hydrogen technologies as an option for the country's energy matrix has risen in the first months of 2021. Discussions have been initiated and a Mexican Hydrogen Association has been formed that brings together private companies and energy agencies, such as the State of Puebla´s, which actively promotes the adoption of green hydrogen. However, there are no national or state guidelines that allow the efforts of stakeholders interested in the subject to be channeled in the same direction.

- **Recommendations:**
  a) Identify the advantages of hydrogen that are compatible with the national development policy embodied in the National Development Plan 2019-2024
  b) Establish country and regional priorities in the development of hydrogen in Mexico (adoption sectors, production technologies, business models, etc.).
  c) Set goals for each identified priority activity. It is recommended that the targets are as quantitative as possible, as this allows constant measurements of compliance and promotes specific demands for hydrogen, which can be translated into technological evolution and cost reduction.
  d) Create a Roadmap or National Strategy that establishes a national vision on how Mexico would participate in the green hydrogen value chain, which are the strategic priorities and which actions must be taken in the short, medium and long term to reach the goals.

- **Benefits:** The greatest benefit of a roadmap is having a national guideline to direct all efforts towards common goals and raise project developer and investor interest. For example, in Japan, efforts are focused on producing hydrogen consumption technologies, while in Chile, a large number of actors are now analyzing projects for hydrogen exports and in other countries such as the United States, a balance between the development of hydrogen production and consumption capacities is seen.

3. The regulation for the use of hydrogen in Mexico is unspecific for mostly all of its possible applications.

- **Impact:** In Mexico 98% of the hydrogen produced and consumed is proprietary of PEMEX, and the remaining 2% is mainly used as a chemical feedstock for industry. Failure to create detailed regulations for the green hydrogen market in energy applications and new chemical applications will be an access barrier for new players, will not lead to the adoption of this substance in more sectors of the economy, and may generate legal controversy when hydrogen technologies compete with conventional technologies. Ambiguities could arise such as categorizing or not hydrogen FCEVs as electric, rules for connecting a fuel cell to the power grid, and considering hydrogen as an energy carrier instead of a chemical feedstock with all the additional regulations necessary.

- **Recommendations:**
  a) Establish market rules for the use of green hydrogen as an energy carrier, as a renewable raw material or chemical feedstock, and for mixed use by the same actor or a consortium of actors.
  b) Include definitions of all hydrogen consumption applications in relevant sectoral legislation: Electric Industry Act (Energy Storage, Network Services), Roads, Bridges and Federal Self-Transport Act (Hydrogen Transport and Hydrogen Electric Mobility), Hydrocarbons Act (Power to Gas Systems, Pipeline Injection).
  c) Modify the Regulations of laws in the economic sectors in which hydrogen participates, or even propose the creation of a Regulation for the Production, Handling, and Use of Green Hydrogen in Mexico.
  d) Create technical regulation that specifies the necessary characteristics of the systems and equipment involved in the production, handling, and consumption of hydrogen.

- **Benefits:** Market regulation will allow to establish guidelines to which stakeholders can adhere to and participate in commercial activities related to green hydrogen, thus providing certainty, and promoting the development of this new market.

4.2 Economic and Political Context

4. Mexico's access to low-cost natural gas from the U.S. poses challenges in green hydrogen's competitiveness.

- **Impact:** As there is a low-cost fossil fuel and raw material to produce gray hydrogen,green hydrogen may take longer to achieve cost parity with it, thus delaying its penetration into the Mexican market.

- **Recommendations:**
  - a) Include the role of green hydrogen in meeting Target #1 for the welfare of the Sectoral Energy Plan 2020-2024, aimed at "Achieving and maintaining sustainable energy self-sufficiency to meet the energy demand of the nation".
  - b) Establish fiscal mechanisms for imported natural gas that finance the deployment of natural gas replacement technologies, such as green hydrogen.

- **Benefits:** These measures would accelerate the economic competitiveness of green hydrogen against natural gas and create a financing mechanism for the national development of technologies and integration of renewable gas generation projects.

5. In Mexico, access to energy infrastructure presents significant entry barriers for new renewable energy-derived projects.

- **Impacts:** Large green hydrogen generation projects will require access to infrastructure such as electric power transmission and distribution networks for hydrogen storage and re-electrification or pipelines for power to gas and green hydrogen methanation.

- **Recommendations:**
  - a) Creation of specific regulations for access to energy infrastructure to foster the integration of green hydrogen projects.
  - b) Establish collaborative programs between state-owned enterprises and small and medium-sized enterprise for the integration of green hydrogen adoption projects.

- **Benefits:** allowing more actors access to the country's energy infrastructure will allow national hydrogen demand to increase in the face of the largest number of possible projects achievable and promote competitiveness, while this penetration reduces emissions from sectors such as oil and gas and power generation.

6. The geographic availability of renewable energy generation plants in Mexico does not necessarily match with the most suitable hydrogen demand for the deployment of large-scale green hydrogen projects.

- **Impact:** Hydrogen production will need sufficient renewable electrical production capacity to ensure that the molecule has "green" characteristics. If renewable energy is not present the development of green hydrogen would be limited and Mexico could miss the opportunity that its high solar and wind potentials provide.

- **Recommendations:**
  - a) Continue with a strong policy of promoting renewable energy, in parallel with the national policy of the adoption of green hydrogen. A green hydrogen strategy is, in a more general view, a strategy of harnessing renewable energy through a chemical molecule that allows the integration of sectors (renewable energy with the electricity, oil and gas, chemical, mining, steel sector, etc.).

  - b) Establish Guarantees of Origin systems for green hydrogen to:
    - i. Establish the criteria for considering hydrogen as "green", based on the targets of decarbonization by sector and the potential of hydrogen to be adopted in it.

    - ii. Generate a differentiated market for highly renewable hydrogen over high carbon footprint gray hydrogen. This will allow producers to compete and sell green hydrogen at prices that allow the recovery of infrastructure investment.

    - iii. Mexico's participation in international green hydrogen markets, where certificates of guarantee of origin will be necessary to ensure that gas destination countries that by acquiring this molecule, they are contributing to global decarbonization and complying with local regulation.

    - iv. Actively encourage hydrogen producers to adopt green hydrogen over other alternatives, given the competitive advantages this type of hydrogen will give them with clear incentive mechanisms.

- **Benefits:** Stimulating the deployment of renewable energy with hydrogen production will enhance economic development and job creation in the energy sector, accelerate the fulfillment of the country's decarbonization targets and enable Mexico to participate in future international green hydrogen markets.

In addition, the same hydrogen technologies may be able to mitigate the natural intermittency of renewable sources such as wind and solar photovoltaic, allowing greater participation of them in the Mexican electricity matrix without compromising the reliability of the National Electricity System.

7. There is a wide cost-competitiveness gap between green hydrogen production and consumption technologies compared to conventional alternatives.

- **Impacts:** High technology costs prevent decision makers from inclining over conventional technologies with green hydrogen. As a result, the demand for hydrogen production and handling equipment does not increase and costs take longer to decline.

- **Recommendations:**
  - **a)** Provide hydrogen technologies financial assistance, which may come from:

    i. Government agencies through loans, subsidies, accelerated depreciation mechanisms or other fiscal stimulus that favor green hydrogen projects.

    ii. Public - private funds financing early-stage hydrogen development projects, such as the European Union's Fuel Cell and Hydrogen Joint Undertaking (FCH-JU).

    iii. Funding through public, multilateral, or private banking through preferential rate financing schemes for the development of green hydrogen projects.

  - **b)** Local production of technologies– Developing local production capacities can reduce the price of goods by reducing transportation costs and eliminating differences in cost per exchange rate between currencies. This measure may delay the adoption of hydrogen technologies in countries such as Mexico, which currently has low productive capacities of hydrogen technologies, so it is advisable to plan local productive activities for the medium term.

  - **c)** Support for research and development projects: considering that the costs of technologies will reduce when their performance improves, it becomes necessary to invest in strategic research and development projects that seek to improve key indicators of hydrogen technologies, such as shelf life, energy efficiency, amount of precious metals, etc.

- **Benefits:** Cost reduction will accelerate the adoption of hydrogen technologies and result in a virtuous circle for decarbonization, in which green hydrogen gains market share by being economically competitive and that reduces greenhouse gas emissions in national inventory.

4.3. Technology and Human Capital

8. Barriers of knowledge about the uses of hydrogen and its potential impacts.

- **Impacts:** Lack of knowledge about the possibilities and potential for green hydrogen adoption in different economic sectors limits the participation of more actors in the hydrogen economy and delays demand for green hydrogen from increasing in the short to medium term.

- **Recommendations:**
  - **a)** Dissemination and communication campaigns: that allow potential stakeholders to discover what applications can have green hydrogen in their industry, what elements are needed to develop projects and what would be the benefits for their business of participating in the hydrogen economy.

  - **b)** Discussion tables between stakeholders from different sectors of the energy sector, where they manifest their ideas, discover the possibility of collaboration in joint projects and present their experiences with the adoption of other technologies in the past.

  - **c)** Learning missions: organize learning missions where Mexican delegations from specific sectors (e.g. steel production, refining or mobility) can visit other countries and are shown in the field the development of technologies and are labeled specific problems that were had in the place visited when a certain application of green hydrogen was implemented.

  - **d)** Create international partnerships that include knowledge transfer programs and lessons learned to Mexico in the adoption of green hydrogen. It is suggested that these programs include as many members as possible in the hydrogen value chain, including regulation, technical regulation, and public policy.

- **Benefits:** Reducing Mexico's learning curve will result in accelerated adoption of green hydrogen, with more agile and less tripping projects, by leveraging the experience of third parties.

9. Limited or disengaged human resources from the energy sector trained in green hydrogen

- **Impacts:** Not having human resources experienced in hydrogen technologies or not actively being part of the energy sector could lengthen project execution times, resulting in slow adoption of green hydrogen and lowering the country's competitiveness in the international hydrogen ecosystem.

- **Recommendations:**
  a) Identification of the status of human resources in hydrogen in Mexico to understand the point of departure.

  b) Analysis of capacities needed to develop the hydrogen economy in Mexico according to the country's vision in this regard.

  c) Creation of training programs aimed at underpinning the skills lacking in the sector.

  d) Creation of innovation and development programs with specific objectives raised from hydrogen adoption management bodies. This will promote scientific action and technology transfer in an aligned manner to Mexico's plan against hydrogen and common objectives.

- **Benefits:** Developing the human capacities needed for green hydrogen has a direct benefit to project development and market creation, however it also promotes the creation of better-paying jobs and reduces Mexico's intellectual and technological dependence on foreign actors.

4.4. International Experiences

Other actions based on experiences of other countries and regions of the world could enhance the development of hydrogen technologies, depending on the national hydrogen policy. Many of these recommendations overlap with those described above, reflecting their alignment with international experience and best practices.

Governance and policy creation

- Actively seek advice and engagement from civil society and industry actors.
- Introduce hydrogen as a measure to enhance energy security.
- Create policies to leverage and re-engineer existing energy infrastructure to make it compatible with green hydrogen.
- Establish carbon prices and policies that promote the replacement of fossil fuels with alternative lower carbon fuels, such as green hydrogen and syn-fuels.

Promotion to electrolysis systems

- Set installed capacity targets for hydrogen production infrastructure over defined time horizons (2025, 2030 or 2050).
- Develop tax schemes and incentives that favor the development of electrolysis and other hydrogen infrastructure projects.
- Increase support for research and development programs that seek to improve the efficiency of these equipment, propose better production methods, and optimize their designs.

Promoting industrial applications of hydrogen

- Moving from extended energy efficiency policies to fuel replacement policies that enable market space for green hydrogen.
- Set ambitious decarbonization goals and create specific financing mechanisms for related projects.
- Create a fair and differentiated market between "regular" products and those with a low carbon footprint and extend the differentiated market between high- and low-carbon products to imported goods, through carbon taxes on products entering the country.

Promotion of hydrogen in air and maritime mobility applications

- Establish a national policy to comply with international emission reduction targets and regulations in these sectors.
- Set explicit targets for reducing aviation and maritime transport emissions and promote synthetic fuels as much as other decarbonized alternatives such as biofuels.
- Provide financial incentives that reduce the cost difference between synthetic fuels and conventional fuels.

5. Identifying capability development needs

Mexico is a country with an economic activity that positions it at site number 15 of the G20 countries and has many intellectual, financial, and legal capabilities developed. However, the adoption of the green hydrogen economy could demand the country to develop new capabilities.

Below are some of the necessary capabilities to be harnessed that have been identified throughout the development of this consultancy.

5.1 Intellectual capabilities

For the adoption of green hydrogen, Mexico could start from a) its widespread human resources base specializing in electricity, oil and gas, renewables, and conventional energy technologies and (b) some human resources that already know hydrogen for its participation in hydrogen production plants of PEMEX or gas companies, for their academic training or for their participation in green hydrogen projects outside Mexico.

The intellectual capabilities identified that Mexico would need to develop are:

a) Public policy specialists for green hydrogen:

People will be needed to understand the dynamics of a molecule within the energy sector, but also within the industrial sector and who can propose policies and regulatory principles for a substance with the characteristics of hydrogen.

b) Technologists at different points in the hydrogen value chain:

For this, Mexico is part of an installed base of scientists and professionals who during their postgraduate studies had interaction with hydrogen technologies (according to information from the Mexican Hydrogen Society, SMH). However, many of them have never participated in the development of an industrial-scale project, so they will need to expand their knowledge on the subject, while in Mexico more widespread human resources training plans are created.

c) Health, Safety & Environment (HSE) specialists:

Mexico handles volumes of between 250 and 300 thousand tons annually and there has never been an accident because of it. However, this hydrogen is produced in just a few plants. Mexico will need to establish technical regulation on safety and more people to train on the issue. Hydrogen safety specialists with experience in today's Mexican plants will be able to serve as instructors and supervisors in the early stages of technological deployment.

d) Hydrogen market researchers and data analysts:

Energy market specialists will be able to expand their knowledge and integrate green hydrogen into their analyses, however, they will need to develop new knowledge, as hydrogen will behave in international markets differently from fossil fuels, and in national markets, their routes of origin and destination will be more diverse due to their duality energy/raw material.

e) Hydrogen communication experts:

Mexico will need to strengthen its social communication capabilities to clearly convey the uses of hydrogen, its risks, limitations and benefits; in the first instance to the actors involved in government, industry, academia, NGOs, and civil society.

5.2 Financial Capabilities

With regard to financial measures, Mexico shall develop capacities with respect to:

a) Specialists in public policies for the green hydrogen:

People who understand the dynamics of a molecule within the sector energy, but also within the sector industry and that can propose policies and regulatory principles for hydrogen

b) Create “friendly” financing mechanisms

With green hydrogen projects that allow developing projects and reducing costs of hydrogen that promotes competitiveness and guarantees the same level playing field for all the actors involved.

The later allows the allocation of capital in hydrogen infrastructure projects and an alignment with international markets and best practices.

c) Quantification of externalities and/or co-benefits:

Hydrogen projects can be given profitability by quantifying the negative impact of traditional fuel use or measuring the transitional benefit to cleaner fuels. That is: assigning a cost to the damage to the environment or health that the use of fossil fuels entails, or quantifying job creation, market creation, the value of learning, emission reduction.

Mexico should generate capacities for the generation of new models of costing and project profiting.

d) Access to international funds for hydrogen development in Mexico:

There are different funds in the world for international cooperation in the development of the hydrogen economy. Mexico will need to learn in the short term what these funds are, how they work, what kind of projects and with what features they can access and what are the steps to apply for them.

5.3 Legal capabilities

It is identified that in Mexico there is a robust legal and law enforcement framework, which can deal with dissents objectively and in reasonable times for the energy sector. Some of the capabilities to be developed in the legal and regulatory areas are:

a) Energy, environment, and industry law experts will need to participate in the formulation of the new regulatory framework for green hydrogen and practicians should learn from international best practices to define and execute following the future market guidelines in Mexico.

b) The strengthening of autonomous regulatory bodies that provide certainty, promote competitiveness, and ensure a fair playing field for all actors involved is necessary to allow the allocation of capital in hydrogen infrastructure projects and an alignment with international markets and best practices.

c) Mechanisms to promote legal best practices and the inclusion of inputs from stakeholders involved in the hydrogen vale chain, including industry, academy, NGOs, and civil society in the law-making processes for matters concerning green hydrogen markets and infrastructure.

5.4 Commercial capabilities

Some capabilities that Mexico will need to develop in the commercial field are:

a) Internally:

Ability to create differentiated markets between products with a regular carbon footprint and one with a low footprint, where there are sufficient advantages for low carbon products.

b) Externally:

Mexico has a high potential for hydrogen production and a lot of experience with international marketing of energy molecules. Mexico will need to extrapolate this hydrogen experience and develop green hydrogen export capabilities. To do this, a deep understanding of what these potential markets are, who are the competitors and what advantages Mexico could have over them in each destination.

6. Potential for Mexican contribution to international hydrogen and energy transition needs

Some of the countries which have established ambitious hydrogen adoption recognize their lack of capacity to be self-sufficient in producing the amounts required to meet their goals. These countries include land-constrained nations such as Korea and Japan, as well as those with the most ambitious goals for adoption such as Germany and other European nations, which have already set in place mechanisms to promote the development and deployment of green hydrogen technologies on a large scale.

Furthermore, countries with abundant renewable energy resources could produce green hydrogen at prices low enough to compete in export markets, which are expected to grow at a rapid face starting from this decade. Mexico's privileged geographic position and abundant renewable energy resources could place it as an exporter of green hydrogen, which is the focus of study of this chapter.

6.1. The hydrogen export market

Around the world hydrogen strategies have been established which will drive the yearly demand by 2030 of nearly 16 million ton per year of green hydrogen in Europe, and of lower emissions hydrogen[11] adding up to 21 million ton in the United States and Canada, 300 thousand ton in Japan, 35 million ton in China, and by 2040 if 5 million ton in South Korea[12]. In Europe, the largest objective demands come from Italy and France, with 2.2 and 2.1 million ton each, followed by the UK and Germany, both with goals of 1.6 million ton, then Spain and the Netherlands with 1.3 million ton each, and finally Portugal and Finland with 0.8 and 0.3 million ton, respectively.

Hydrogen demand globally is expected to experience an accelerated growth, accumulating all production technologies, going from 75 million ton in 2020 according to the International Energy Agency (IEA), to a range between 90 and 100 million ton in 2030 and between 280 to nearly 700 million ton by 2050, following projections of the IEA, the International Renewable Energy Agency (IRENA), the Hydrogen Council, and Bloomberg New Energy Finance (BNEF).

For reference, Mexico's current hydrogen demand is below 230 thousand ton per year, and the projected demands are indicative of a growing global hydrogen market which will develop with rising opportunities for low-cost green hydrogen producing countries for export. Renewable energy rich countries such as Australia, Chile, Morocco, and Saudi Arabia, among other, have either set strategies or announced large-scale hydrogen production projects for exports, which are set in the billions of dollars of expected investment in hydrogen producing infrastructure dedicated for export.

6.2. Overseas hydrogen export analysis

A comparative analysis was performed to assess the cost competitiveness of a number of exporting routes, that is, from a set of producing (exporting) countries to hydrogen consuming (importing) countries.

The potential hydrogen importers considered are Japan, South Korea, the United Kingdom, and the European Union as a whole. The projected hydrogen demand and an average local Levelized Cost of Hydrogen (LCOH) were considered to prioritize them. Similarly, the potential hydrogen exporters studied include Australia, Chile, Mexico, and Morocco and were assessed by the expected average LCOH of the hydrogen produced locally as well as the production capacity for export.

The demand and production capacity projections come from each country's hydrogen strategy or roadmap and institutional or industry reports from national and international organisms such as the IEA, while local LCOH for each country was obtained using Hinicio models. Additionally, a port of export or import of hydrogen was designated for each country to calculate shipping route distance and costs. The characterization of potential green hydrogen importing and exporting countries is shown in the following tables.

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[11] Lower emissions hydrogen consists mainly of green hydrogen, produced with renewable powered electrolysis and blue hydrogen, conventional hydrogen production from natural gas or coal coupled with carbon capture technologies. Some national hydrogen strategies have not established specific goals for each of the technologies, while the EU is targeting only green H2.

[12] Hydrogen demand objectives are taken from each country's H2 roadmap. For China, the references are the Chinese National Alliance of Hydrogen and Fuel Cell and Energy Saving and New Energy Vehicle Technology Roadmap. South Korea's roadmap sets 2040 targets.

Table 6-1. Characterization of potential hydrogen importing countries.

	Importing Countries	**Potential**		
#	**Country**	LCOH 2030 (USD/kgH_2)	H_2 demand 2030 (kton/year)	Destination Port
1	**European Union**	> 4	20,000	Rotterdam
2	**Japan**	6.5	>300	Osaka
3	**South Korea**	> 4	1,940	Busan
4	**United Kingdom**	> 4	~700	Felixstowe

All of the import countries display levelized costs of hydrogen considerably higher than the LCOH of hydrogen produced by exporters in 2030. The largest projected hydrogen demand is in the European Union, followed by South Korea. Japan's demand is projected to be smaller but with a high potential for receiving imports given the high cost of producing it locally at the highest cost of 6.5 USD/kgH_2, as shown in Table 6-1.

Table 6-2. Characterization of potential hydrogen exporting countries.

	Exporting Countries	**Potential**		
#	**Country**	LCOH 2030 (USD/kgH_2)	H_2 offer 2030(kton/year)	Port of Orifgin
1	**Australia**	2.41	500	Darwin Port
2	**Chile**	2.14	< 1,000	Antofagasta
3	**Mexico**	2.32	Unknown	Ensenada / Altamira
4	**Marruecos**	2.22	Unknown	Casablanca

It can be seen from Table 6-2 that all exporting countries have LCOH much lower than the importing countries, at competitive values hovering around Mexico's 2.32 USD/kgH_2 and varying no more than 13% within the highest and lowest projected LCOHs. The production capacities are either unknown or by exceed the expected amount of hydrogen the target countries could receive from imports, so the main factors for determining cost at the port of delivery are production LCOH and transport distance. To calculate shipping distances, a matrix was built with the distances in nautical miles between all possible port combination, shown in the following table.

Table 6-3. Port to port distance table. Units are nautical miles (NM)

Distance (NM)	**Origin**			
Destination	Australia	Chile	Mexico	Morocco
European Union	10,078	7,456	5,104	1,413
United Kingdom	10,071	7,449	5,035	1,407
Japan	2,942	9,534	5,249	9,819
South Korea	2,929	9,824	5,369	9,613

Finally, taking as input the production LCOH at exporting countries, a final LCOH delivered at the import destination was calculated for each export-import country combination. The results are shown in Table 6-4, using a color scale to highlight the competitiveness of the hydrogen trade route, with green being the lowest LCOH at the destination port, and red the highest LCOH and least competitive routes.

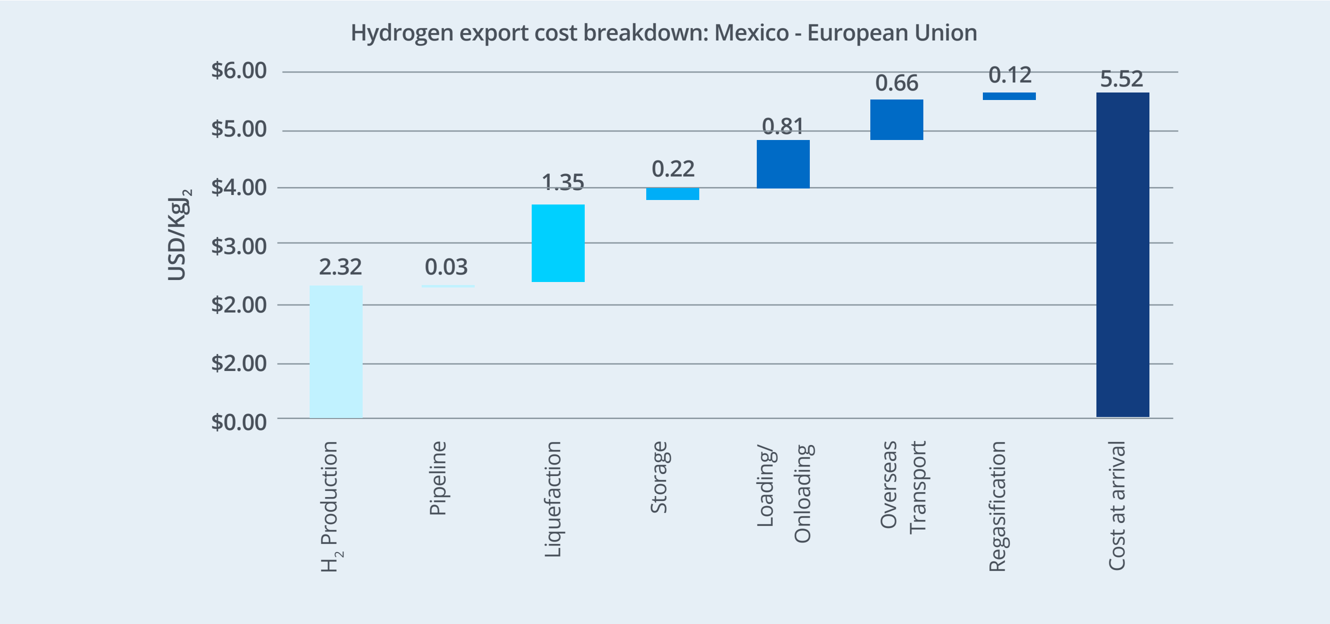
Table 6-4. Projected LCOH at the port of destination for each hydrogen trade route, with Mexico's ranking withing the studied exporters for each destination.

LCOH (USD/kgH_2)	**Origin**				**Mexico´s Ranking**
Destination	Australia	Chile	Mexico	Morocco	
European Union	6.15	5.32	5.52	4.78	3
Japan	5.38	5.65	5.60	5.78	2
South Korea	5.29	5.65	5.53	5.67	2
United Kingdom	6.25	5.41	5.60	4.87	3

A breakdown of the costs of the hydrogen delivered at port divides them into hydrogen production, conversion into liquid hydrogen for shipping, export and import terminal costs, maritime transport, reconversion to gaseous hydrogen, and distribution to delivery point at the port of destination. For simplicity, many of the costs are considered to be the same regardless of the ports and route involved, namely conversion and reconversion, terminal tariffs and distribution costs, which account for roughly half of the cost at destination. That is, around half of the costs are fixed and half vary with local production of hydrogen and shipping distance, which accounts for the differences in cost depending on the country of origin and destination.

For example, when exporting from Mexico to the European Union around 40% of the cost is the production of hydrogen and 10% corresponds to the maritime transport. Conversion and reconversion account for nearly 30% of the cost, terminal tariffs for approximately 20%, and marginal share of under 2% goes to distribution, as shown in Figure 6-1.

Figure 6-1. Hydrogen export breakdown by cost components from Mexico to the EU.



The most competitive hydrogen cots at destination are provided by the shortest shipping routes which are, respectively, to Japan and South Korea from Australia, and to the European Union and the UK from Morocco. Conversely, the highest costs at delivery correspond to the longest routes. Mexico the second most competitive exporter to Asian destinations and the third to European markets in the study, given a low H_2 production cost, its privileged geographic position with access to both the Atlantic and the Pacific Oceans, and its northern latitude shortening shipping distance to the main importers.

Further analysis is made focused on Mexico to estimate the share of the hydrogen demand that Mexico could supply to the target overseas markets in this study, which translates into a hydrogen exports by 2030 of 60 thousand ton with a yearly market value of 330 million USD and requiring nearly 700 MW of electrolysis to produce.

Table 6-5. Projected overseas hydrogen exports from Mexico in 2030.

Market	H_2 demand 2030 (kton/year)	H_2 supply (kton/year)	Market share (%)	Electrolysis (MW)	Market Value (MMUSD/year)
EU	20,000	9.94	0.05%	116	58
Japan	300	19.88	6.6%	231	111
South Korea	1,940	19.88	1.0%	231	110
UK	700	9.94	1.4%	116	56

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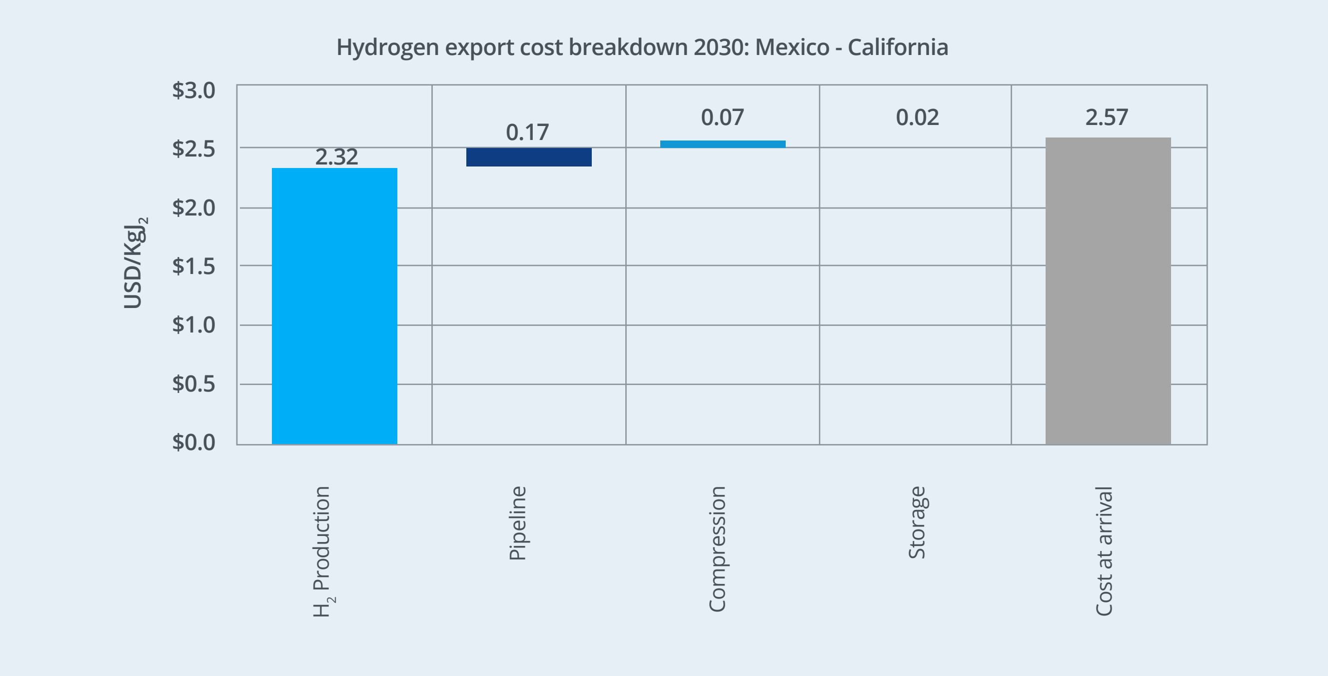
[10] El costo de entrega es el LCOH en el puerto de destino, e incluye los costos de producción, transporte en ducto, conversión y reconversión de H_2 de gas comprimido a líquido (licuefacción y regasificación), transporte marítimo en buque, y costos de terminales de exportación e importación.

Hydrogen exports from Mexico to Japan and South Korea could be the most competitive and account for a trade value of over 200 MMUSD per year by 2030.

6.3 Green hydrogen export by pipeline

An additional analysis was made to assess the export of green hydrogen from Mexico to California by land through pipelines. The assessment assumes a short distance travelled by pipeline of under 200 km, meaning both the sites and of hydrogen production and of delivery should be relatively close to the binational border; and leaves out cost components from the overseas export analysis such as the conversion and reconversion to a liquid carrier, terminals, and maritime shipping, yielding a much lower cost of hydrogen delivered at site starting with a 2.32 USD/kg for producing green hydrogen in 2030. The results show a cost of hydrogen delivered where transport by pipeline adds only 10% to the final cost, meaning its mostly dependent on the cost of production alone. Mexico could deliver green H_2 by pipeline to California as cheap as 2.57 USD/kg in 2030.

Figure 6-2. Hydrogen export by pipeline breakdown by cost components from Mexico to California, USA in 2030.



7. Conclusions

The hydrogen economy in Mexico could have significant impacts across a broad range of areas, including manufacturing, climate mitigation, job creation, business opportunities locally and in international trade, regulatory and financial strengthening and capacity building.

In manufacture of hydrogen technologies, the analysis shows Mexico as a country with potential to be competitive in the manufacture of hydrogen power turbines as well as conditioning, transport, and storage equipment. The automotive industry could continue to thrive in the country, leveraging on a robust manufacturing ecosystem to adopt new hydrogen FCEV technologies. Mexico displays the potential to position itself as a leading manufacturer of FCEVs worldwide.

Regarding GHG emissions reduction, the CO_2 avoided by the introduction of green hydrogen by PEMEX in refineries and ammonia production in Mexico would reach more than 3.2 million $tonCO_2e$/year by 2050. Replacing fossil fuels with green hydrogen for applications in power generation and industry has the potential of reducing up to 7.6 million $tonCO_2e$/year in 2050. By 2050, substituting ICEVs with FCEVs in heavy-duty public and freight transport and diesel with syn-fuels in aviation could reduce GHG emissions by up to 26.7 $tonCO_2e$/year.

In job creation, over 90,000 jobs could be created in Mexico by 2050. The largest area of job creation is in the production of hydrogen itself and the required infrastructure. The second largest area of employment would be in the hydrogen refueling infrastructure, and thirdly, the automotive industry for heavy-duty FCEV production.

As for market creation and investment, the joint expected impact for PEMEX and CFE is of roughly 100 million USD per year by 2030 and more than 1.3 billion USD yearly by 2050 to supply their hydrogen demand. The largest projected opportunities in hydrogen for the private industries are in FC CAEX and mineral ore reduction, which jointly account for nearly 80% of the economic impact of the market, valued at 800 million USD/year by 2050. Cumulative investments for supplying hydrogen to PEMEX and CFE are projected in close to 2.6 billion by mid-century, and in nearly 8.5 billion to supply the private industry.

Concerning regulatory and financial recommendations to enhance hydrogen production in Mexico, the country should introduce green hydrogen uses in its climate policy, promote renewable energies from political and regulatory standpoints, and develop a National Hydrogen Roadmap with defined targets and actions. Finally, funding should be allocated or facilitated for the development and adoption of green hydrogen infrastructure and technologies.

Mexico has many capabilities in the energy and industry sectors already well developed. However, the adoption of the green hydrogen economy will demand the country do capacity building by developing new qualified human resources, as well as expanding financial, legal, and commercial capabilities.

Mexico’s abundant renewable energy resources and privileged position provide it with a great potential to export hydrogen to international markets, mainly in Europe and Asia, thus further creating business opportunities and contribute to international hydrogen and energy transition needs with a target market of 330 million USD by 2030 and the potential to export by pipeline to California at a competitive cost.

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